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A Comprehensive Experimental Evaluation of Test Maneuvers That May Induce On-Road, Untripped, Light Vehicle Rollover

Phase IV of NHTSA's Light Vehicle Rollover Research Program

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16. Abstract

In Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" Congress directed the National Highway Traffic Safety Administration (NHTSA) to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover propensity rating test is to be incorporated into NHTSA's New Car Assessment Program (NCAP). The research described in this report, which is Phase IV of NHTSA's Rollover Research program, has been performed as part of NHTSA's effort to fulfill the requirements of the TREAD Act.

Phase IV testing was performed during the spring through fall of 2001. The objective of this testing was to obtain the data needed to down select from a candidate set of dynamic rollover maneuvers to a more limited set that characterize vehicles' rollover resistance. Five Characterization maneuvers (only one of the Characterization maneuvers, Slowly Increasing Steer, is discussed in this report) and eight Rollover Resistance maneuvers were evaluated. Each Rollover Resistance maneuver was evaluated based upon its Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality. For each maneuver evaluation factor, the authors assigned an adjectival rating of Excellent, Good, Satisfactory, Bad, or Very Bad.

Four sport utility vehicles were tested, a 2001 Chevrolet Blazer, a 2001 Toyota 4Runner, a 2001 Ford Escape, and a 1999 Mercedes ML320. Two of these (the 4Runner and the ML320) were equipped with electronic stability control systems.

A detailed description of the testing performed and the results obtained is presented. For the one Characterization and each of the eight Rollover Resistance maneuvers, the maneuver is described, input and output repeatability are discussed, and testing results are presented. For the Rollover Resistance maneuvers, a discussion of the reasons for the adjectival rating assigned for each maneuver evaluation factor is presented.

Four of the Rollover Resistance maneuvers have a rating of satisfactory or better for each of the four maneuver evaluation factors. In the authors' opinion, maneuvers now exist that are refined enough to be used by the Government for either regulation or consumer information.

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in	inches	25.4	millimeters	mm	mm	millimeters	0.04	inches	in
in	inches	2.54	centimeters	cm	cm	centimeters	0.39	inches	in
ft	feet	30.48	centimeters	cm	m	meters	3.3	feet	ft
mi	miles	1.61	kilometers	km	km	kilometers	0.62	miles	mi
		AREA					AREA		
in^2	square inches	6.45	square centimeters	cm^2	cm^2	square centimeters	0.16	square inches	in^2
ft^2	square feet	0.09	square meters	m^2	m^2	square meters	10.76	square feet	ft^2
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)					MASS (weight)		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.45	kilograms	kg	kg	kilograms	2.2	pounds	lb
		PRESSURE					PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar	bar	bar	14.50	pounds per $inch^2$	psi
psi	pounds per $inch^2$	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY					VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h	km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION					ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2	m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C	°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

DISCLAIMER

NOTE REGARDING COMPLIANCE WITH AMERICANS WITH DISABILITIES ACT SECTION 508

For the convenience of visually impaired readers, descriptive text of the figures contained in this document have been included to satisfy Section 508 of the Americans With Disabilities Act (ADA). These descriptions are for the benefit of visually impaired readers using text-to-speech software, and have been included in the Appendix of this document.

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The research documented in this report was a coordinated effort by the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VTRC) and the Transportation Research Center Inc. (TRC) to evaluate maneuvers used to assess light vehicle dynamic rollover propensity. Using results from this research, the authors were able to select maneuvers believed to be satisfactory for either Government regulation or consumer information.

The authors wish to recognize the outstanding support of our research colleagues. Pat Boyd from the NHTSA Safety Performance Standards office contributed to the development of the test procedures used in this study. Larry Jolliff, Randy Landes, and Roger Schroer performed the driving required by the rollover program. Greg Stevens, Jim Preston, Michael Brown, Adam Andrella prepared the vehicles for testing by installing instrumentation and outriggers, and assisted with the many necessary tire changes. Devin Elsasser, Dave Dashner, and Leslie Portwood performed post-processing of the test and video data. Jan Cooper provided administrative support.

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EXECUTIVE SUMMARY

Introduction

This research evaluated maneuvers used to assess light vehicle dynamic rollover propensity. Even though all types of rollover are dynamic events, the focus of this investigation, dynamic rollover, is generally construed as on-road, untripped, rollover. While on-road, untripped rollovers are responsible for only a small portion of the rollover safety problem for this classification of vehicles; there are enough fatalities due to these crashes that even a small portion of the problem equates to a substantial number of fatalities per year. Further, the authors hope that understanding the causes of this type of rollover will assist with rollover prevention in general.

In Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" Congress directed the National Highway Traffic Safety Administration (NHTSA) to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into NHTSA's New Car Assessment Program (NCAP) by November 1, 2002. The research described in this report has been performed as part of NHTSA's effort to fulfill the requirements of the TREAD Act.

Objectives

Prior to the initiation of the Phase IV research, NHTSA met with the Alliance of Automobile Manufacturers, Ford Motor Company, Nissan Motors, Toyota Motor Company, Consumers Union of the United States, MTS Systems Corporation, and other interested parties to gather information on possible approaches for dynamic rollover tests. NHTSA also corresponded with the University of Michigan Transportation Research Institute and Heitz Automotive, Inc. These parties made specific suggestions about approaches to dynamic testing of vehicle rollover resistance. Based on these suggestions plus NHTSA's experience in this area, the Phase IV test matrix was developed.

Phase IV testing was performed during the spring through fall of 2001. The objective of this testing was to obtain the data needed to reduce from the suggested maneuvers to a more limited set that characterize vehicles' rollover resistance. Five Characterization maneuvers and eight Rollover Resistance maneuvers were evaluated.

Only one Characterization maneuver, Slowly Increasing Steer, is discussed in this report. The others will be discussed in a separate report.

Each Rollover Resistance maneuver was evaluated based upon its Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality. For each maneuver evaluation factor, the authors assigned an adjectival rating of Excellent, Good, Satisfactory, Bad, or Very Bad.

Four sport utility vehicles were tested during Phase IV, a 2001 Chevrolet Blazer, a 2001 Toyota 4Runner, a 2001 Ford Escape, and a 1999 Mercedes ML320. Two of these (the 4Runner and the ML320) were equipped with electronic stability control systems.

Each test vehicle was tested in three configurations. The Nominal Load configuration consisted of the driver, instrumentation, and outriggers. The Reduced Rollover Resistance configuration required sufficient weight be placed on a particular test vehicle's roof to reduce its Static Stability Factor (SSF) by 0.05. The weight on the roof was positioned so that the longitudinal/lateral position of the center of gravity did not change. Depending on the test vehicle, the Modified Handling configuration was achieved in one of two ways. The first technique was to load a vehicle to its rear Gross Axle Weight Rating (GAWR) while simultaneously achieving the Gross Vehicle Weight Rating (GVWR). The load was positioned so that it did not affect the center of gravity height or lateral position in the vehicle, only its longitudinal location. Alternatively, different tires/wheels approved/sold as OEM equipment for a particular vehicle were installed.

All Phase IV tests were performed on the Transportation Research Center, Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The test surface was paved with asphalt of a mix representative of that used to construct many Ohio highways. All Phase IV tests were performed on dry pavement.

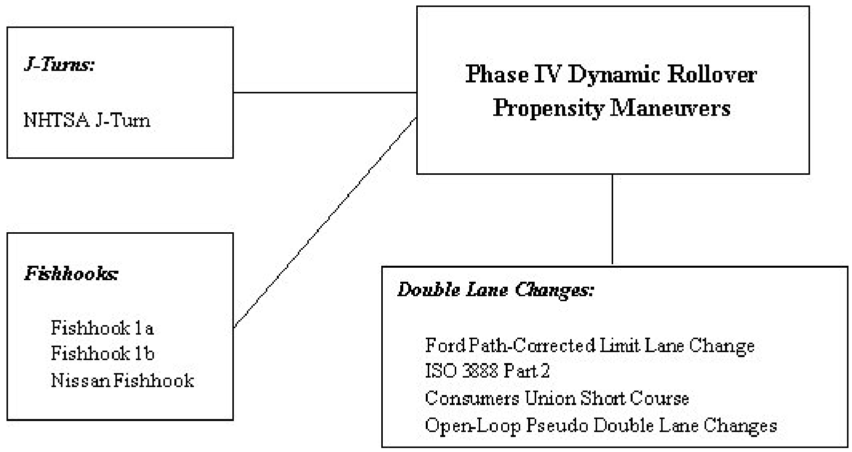
Unlike previous phases, the authors decided not to consider or report minor two-wheel lift in Phase IV. Its occurrence was no longer used as a termination condition for rollover resistance maneuvers. Furthermore, the authors decided not to differentiate between moderate and major two-wheel lift. In this report the term two-wheel lift is used to indicate that either moderate or major two-wheel lift was observed.

Characterization Maneuvers

Five Characterization Maneuvers were studied during the Phase IV research. The Pulse Steer, Sinusoidal Sweep, Slowly Increasing Steer, Slowly Increasing Speed, and J-Turn Response Time test series each included tests performed with the Nominal Load, Reduced Rollover Resistance, and Modified Handling configurations. A programmable steering machine was used to command all Characterization Maneuver handwheel inputs. This report summarizes results obtained from the Slowly Increasing Steer tests, and how the subsequent data is used to define NHTSA J-Turn and Fishhook handwheel input magnitudes. For the sake of brevity, results from the other Characterization Maneuvers will be discussed in a later report.

Rollover Resistance Maneuvers

Eight Rollover Resistance maneuvers were evaluated during the Phase IV research. The maneuvers evaluated were:



A programmable steering machine was used to generate J-Turn, Fishhook, and Open-Loop Pseudo Double Lane Change handwheel inputs. The other three maneuvers were path-following maneuvers with driver-generated, closed-loop, steering. Multiple test drivers were used for the maneuvers with closed-loop steering.

Depending on the maneuver, the test vehicles were evaluated with up to three configurations per maneuver (Nominal Load, Reduced Rollover Resistance, and Modified Handling).

Table 1 summarizes the scores assigned to each Rollover Resistance maneuver in the areas of Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality.

Table 1. Summary of Rollover Resistance Maneuver Scores.

Assessment Criterion	NHTSA J-Turn	Fishhook 1a	Fishhook 1b	Nissan Fishhook	Ford Path-Corrected Limit Lane Change	ISO 3888 Part 2 Double Lane Change	Consumers Union Short Course Double Lane Change	Open-Loop Pseudo-Double Lane Change
Objectivity and Repeatability	Excellent	Excellent	Excellent	Good	Bad	Bad	Bad	Satisfactory
Performability	Excellent	Good	Excellent	Satisfactory	Satisfactory	Good	Satisfactory	Satisfactory
Discriminatory Capability	Excellent*	Excellent	Excellent	Excellent	Good	Very Bad	Very Bad	Very Bad
Appearance of Reality	Good	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent

*When limited to vehicles with low rollover resistance and/or disadvantageous load condition.

Table 2 summarizes the two-wheel lifts that occurred during the Phase IV testing. No two-wheel lift was observed during any "clean" (no cones struck or bypassed) path following, closed-loop steering, double lane change maneuver (i.e., for the ISO 3888 Part 2 and Consumers Union Double Lane Changes), even when the vehicles were evaluated in the Reduced Rollover Resistance condition.

Conclusion

Thirty years ago, NHTSA began studying dynamic rollover propensity maneuvers. At that time, the conclusion reached was that the maneuvers being studied had such major problems, particularly in the area of objectivity and repeatability, as to preclude their use by the Government. Today, following much effort, this is no longer the case. As can be seen from Table 1, four of the Rollover Resistance maneuvers have a rating of satisfactory or better in each of the four maneuver evaluation factors. In the authors' opinion, these four maneuvers are good enough that they could be used by the Government for consumer information.

Table 2. Minimum Maneuver Entrance Speed Resulting in Two-Wheel Lift (mph).

Vehicle	J-Turn	Fishhook 1a	Fishhook 1b	Nissan Fishhook	Ford Path-Corrected Limit Lane Change	ISO 3888 Part 2 Double Lane Change	Consumers Union Short Course Double Lane Change	Open-Loop Pseudo-Double Lane Change	
								Simulated CU Short Course Double Lane Change	Simulated ISO 3888 Part 2 Double Lane Change
2001 Chevrolet Blazer	-- (38.9[1])	40.2 (36.2[1])	40.1 (36.2[1], 34.9[2])	46.1	--	-- (--[1])	--	48.2	54.0
2001 Toyota 4Runner (enabled VSC)	-- (--[1])	-- (47.6[1])	-- (49.6[1], --[2])	Tests not performed.	--	-- (--[1])	--	--	--
2001 Toyota 4Runner (disabled VSC)	-- (46.1[1])	-- (38.4[1])	-- (37.7[1], --[2])		--	-- (--[1])	--	--	42.9
1999 Mercedes ML320 (enabled ESP)	-- (50.9[1])	47.8 (N/A[1])	49.9 (N/A[1], 51.7[2])		--	-- (--[1])	--	Tests not performed.	
1999 Mercedes ML320 (disabled ESP)	-- (45.1[1])	43.5 (N/A[1])	46.4 (N/A[1], 51.3[2])		--	-- (--[1])	--		
2001 Ford Escape	-- (--[1])	-- (48.4[1])	-- (46.0[1], --[2])	--	--	-- (--[1])	--		

Note: Unless indicated, the results presented in Table 2 were observed in the Nominal Load configuration

[1]Reduced Rollover Resistance configuration

[2]Modified Handling configuration

1.0. INTRODUCTION

1.1 Scope of This Investigation

This research evaluated maneuvers used to assess light vehicle dynamic rollover propensity. Light vehicles consist of (1) passenger cars and (2) multipurpose passenger vehicles and trucks (vans, minivans, sport utility vehicles (SUVs)[1], under 4,536 kilograms (10,000 pounds) gross vehicle weight rating (collectively, "light trucks"). While heavy vehicles are also recognized as having significant rollover problems, the causes of heavy vehicle rollover frequently are very different from those of light vehicles due to articulated vehicles (tractor/trailer combinations), major weight shifts that may occur due to loading, etc. Therefore, heavy vehicles were not included in this study. Similarly, motorcycles are fundamentally different than light vehicles with four wheels and therefore were not included.

Rollover crashes can be subdivided into categories depending upon where the rollover occurs and the mechanism that initiated the rollover. The types of rollover crashes and category definitions used in this report are:

- **Off-Road Rollover**. This type of rollover occurs when a vehicle is not on a paved road surface. Due to the large variety of possible tripping mechanisms present in an off-road environment, most of these rollovers occur due to tripping. Note that an off-road rollover can occur while a vehicle is on an unpaved road. Also, it cannot occur while a vehicle is on a paved surface that is not part of the roadway but is designed to be driven on (i.e., rollovers that occur on a paved road shoulder are not off-road rollovers but ones that occur on a paved sidewalk are).

- **On-Road, Tripped, Rollover**. This type of rollover occurs when a vehicle being driven on a paved surface (meant to be driven upon) rolls over due to impact with a tripping mechanism such as a raised manhole cover or a significant pavement discontinuity. A rollover induced by some part of the vehicle, such as a wheel rim digging into the pavement, would also be considered to be an on-road, tripped rollover.

- **On-Road, Untripped, Rollover**. This type of rollover occurs when a vehicle being driven on a paved surface (meant to be driven upon) rolls over without impacting a tripping mechanism. This type of rollover may result from either intentional, driver-controlled, severe vehicle maneuvering or from unintentional, out-of-control, vehicle motions. Review of currently available rollover crash data indicates that approximately two-thirds of on-road rollover crashes are untripped.

Even though all types of rollover are dynamic events, the focus of this investigation, dynamic rollover, is generally construed as on-road, untripped, rollover.

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[1] This report includes the Automotive News category of “sport wagons” in the SUV category.

Perusal of the various rollover crash databases clearly shows that the *off-road* rollover category contains the vast majority of all light vehicle rollover crashes, and that *on-road* rollovers (rollovers due to vehicle maneuvering) represent only a small part of the overall rollover safety problem. However, there are enough fatalities due to rollover crashes that even a small portion of the problem equates to a substantial number of fatalities per year. Further, the authors hope that understanding the causes of this type of rollover will assist with rollover prevention in general.

1.2 The Safety Problem

Rollovers are the second most dangerous type of crash occurring on our nation's highways. Only head-on collisions kill more Americans each year than do rollover crashes.

Three crash databases maintained by the National Highway Traffic Safety Administration (NHTSA) were utilized to determine the magnitude of the light vehicle rollover problem. The databases examined were the Fatality Analysis Reporting System (FARS), the National Automotive Sampling System Crashworthiness Data System (NASS-CDS), and the National Automotive Sampling System General Estimates System (NASS-GES). Analyses of the last two of these databases should provide similar estimates of the size of the rollover problem; differences between the two sets of estimates give some idea of the statistical variability present in the data.

According to the 2000 Fatality Analysis Reporting System (FARS), 9,882 people were killed as occupants in light vehicle rollover crashes, including 8,146 killed in single-vehicle rollover crashes. FARS shows that 53 percent of light vehicle occupant fatalities in single-vehicle crashes involved a rollover event. The proportion differs greatly by vehicle type: 46 percent of passenger car occupant fatalities in single-vehicle crashes involved a rollover event, compared to 63 percent for pickup trucks, 60 percent for vans/minivans, and 78 percent for sport utility vehicles.

According to the National Automotive Sampling System Crashworthiness Data System (NASS-CDS), an estimated 274,000 light vehicles per year were towed from rollover crashes during 1996 through 2000. An estimated 31,000 occupants of these vehicles were seriously injured (defined as an Abbreviated Injury Scale (AIS) rating of at least AIS 3). The above includes 221,000 single-vehicle tow-away rollover crashes. Therefore, 81 percent of tow-away rollovers occurred in single-vehicle crashes. Estimates from NASS-CDS also indicate that 84 percent (186,000) of the single-vehicle rollover crashes occurred after the vehicle left the roadway. An audit of 1992-96 NASS-CDS data showed that about 95 percent of rollovers in single vehicle crashes were tripped by mechanisms such as curbs, soft soil, pot holes, guardrails, and wheel rims digging into the pavement, rather than by tire/road interface friction as is the case for untripped rollover events.

Based on the 1996-2000 National Automotive Sampling System General Estimates System (NASS-GES) data, an estimated average of 61,000 occupants in rollover crashes annually received injuries rated as *K* or *A* on the police *KABCO* injury scale. (The police KABCO scale calls *A* injuries "incapacitating," but their actual severity depends on local reporting practice. An "incapacitating" injury may mean that the injury was visible to the reporting officer or that the officer called for medical assistance. A *K* injury is fatal.) The data indicate that 212,000 single-vehicle rollover crashes resulted in 50,000 *K* or *A* injuries.

Estimates from NASS-GES indicate that 13 percent of light vehicles in police-reported single-vehicle crashes rolled over. The estimated risk of rollover differs by light vehicle type: 10 percent of cars and 10 percent of vans/minivans in police-reported single-vehicle crashes rolled over compared to 18 percent of pickup trucks and 27 percent of SUVs. The percent of all police reported crashes for each vehicle type that resulted in rollover was 1.7 percent for cars, 2.0 percent for vans/minivans, 3.7 percent for pickup trucks and 5.4 percent for SUVs.

1.3 Recent NHTSA Light Vehicle Rollover Research

NHTSA has decided not to proceed with rollover propensity rulemaking based upon either static or dynamic vehicle rollover metrics. This decision was made because even though relatively good correlations between predicted and actual rollover rates existed, none of the metrics provided a sudden transition between good and bad performing vehicles in terms of rollover. As a result, requiring reasonably achievable improvements to any of the static or dynamic vehicle rollover metrics resulted in only a small reduction in rollover crash fatalities. A complete summary of the benefits that the NHTSA expected to obtain from requiring, via an FMVSS, that vehicles exceed specified minimum levels of these rollover metrics is contained in [1].

In July 1996, the NHTSA decided to initiate a rollover propensity research program focusing on on-road, untripped, rollover. Sections 1.3.1 through 1.3.6 describe NHTSA's rollover research efforts from the late 1990's through the early 2000's.

1.3.1 Isuzu Trooper Testing

Prior to the initiation of the new rollover propensity research program, the NHTSA received two petitions from Consumers Union of the United States. One petition, which was granted, requested that NHTSA establish a consumer information program on rollover resistance. The second petition, which was denied, requested that NHTSA open a defect investigation as to whether 1995 and 1996 model year Isuzu Troopers and 1996 model year Acura SLXs had an unreasonably high rollover propensity. The testing performed by the NHTSA to formulate a response to the second Consumers Union petition is documented in [2] and [3]. The principal findings of this research that are relevant to the current study were:

1. There exist maneuvers that induce large (i.e., both wheels off of the ground by substantial amounts) two-wheel lifts for at least some modern sport utility vehicles. This finding is consistent with results from the 1971 - 1974 rollover research and indicates that the results of the 1971 - 1974 research apply to modern vehicles.

2. A vehicle's rollover (two-wheel lift) behavior in a complex maneuver (such as a double lane change) depends strongly upon the precise steering inputs provided by the driver. At a given speed, a driver can use different sets of steering inputs to attempt to follow the same course. These different sets of steering inputs can result in a vehicle having a completely different rollover behavior. For example, one set of steering inputs may allow the driver to proceed completely through a course without any two-wheel lift while a second set of steering inputs, at the same speed, may result in large two-wheel lift and rollover (making it close to impossible to drive the specified trajectory). Again, this finding is consistent with results from the 1971 - 1974 rollover research programs.

Starting in 1997, NHTSA began another light vehicle rollover research program. This research program has been performed in a series of phases. This program was not all planned in advance; instead additional phases were added at the conclusion of prior phases. Phases that have either been performed for NHTSA's 1997 Light Vehicle Rollover Research program are:

1.3.2 Phase I-A: Maneuver Selection and Procedure Development

The Phase I-A testing was performed during the spring through fall of 1997. This phase was an initial, exploratory study of using test track maneuvers to quantify on-road, untripped rollover propensity. This study examined a broad range of maneuvers believed to potentially induce on-road, untripped, rollover. A total of eight test procedures were evaluated: J-Turn (without pulse braking), J-Turn with Pulse Braking, Brake and Steer, Steering Reversal, Toyota Fishhook (without pulse braking), Double Lane Change, Split-Mu Two Wheels Off-Road Recovery Simulation, and Toyota Fishhook with Pulse Braking. Each maneuver was either discarded or retained for further study in subsequent program phases. Maneuvers were evaluated based upon:

1. Their objectivity and repeatability, i.e., whether they could be performed objectively, with repeatable results for the same vehicle.

2. Their discriminatory capability, i.e., whether they resulted in on-road untripped rollover for some, but not all, vehicles.

3. Their appearance of reality, i.e., whether they might be performed by actual drivers while driving (particularly in emergencies).

4. Their metric measurement capability, i.e., whether one or more metrics that are expected to quantify a vehicle's rollover propensity can be calculated from data collected during the maneuver.

The results of the Phase I-A research are documented in the NHTSA Technical Report "An Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped, Light Vehicle Rollover - Phase I-A of NHTSA's 1997-1998 Vehicle Rollover Research Program" [4].

1.3.3 Phase I-B: Maneuver and Procedure Finalization

Preliminary analysis of the Phase I-A results revealed a number of issues that had to be resolved before the Phase II testing could begin. Therefore, the Phase I-B testing was performed during the winter of 1997 and the spring of 1998. The objectives of the Phase I-B research were to:

1. Develop an understanding of the effects of driver variability, outriggers, and fuel level on the results from individual tests. Test procedures were then modified so as to minimize these effects.

2. Develop the Resonant Steer maneuver as a test for examining whether or not steering repeated sinusoidal cycles at a vehicle's fundamental roll frequency would result in a substantially decreased rollover resistance.

3. Procure a programmable steering controller and determine the precise steering inputs to be used as a function of time for each of the maneuvers that were to be used during Phase II.

4. Finalize the maneuvers and procedures that were used during Phase II of the Light Vehicle Research program.

The results of the Phase I-B research are documented in the NHTSA Technical Report "An Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped, Light Vehicle Rollover - Phase I-B of NHTSA's 1997-1998 Vehicle Rollover Research Program" [5].

1.3.4 Phase II: Fleet Characterization

The objectives of Phase II of the Light Vehicle Rollover Research program were:

1. To experimentally determine the rollover resistance of a broad range of light vehicle classes and, within classes, vehicle sizes using the test maneuvers and procedures developed during Phases I-A and I-B of the Light Vehicle Rollover Research program.

2. To use the results from this testing to characterize the on-road, untripped rollover propensities of a broad range of light vehicles.

3. To compare the on-road, untripped rollover propensities of a broad range of light vehicles with their static and dynamic rollover metrics (Static Stability Factor, Tilt Table Ratio, and Critical Sliding Velocity).

4. To use the results from this testing to improve the test maneuvers and procedures used to characterize the on-road, untripped, rollover propensities of light vehicles.

Testing for Phase II of NHTSA's Vehicle Rollover Research program was performed from June through September of 1998. Data reduction and analysis were performed from September through December of the same year. The results of the Phase II research are documented in the NHTSA Technical Report "An Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped, Light Vehicle Rollover - Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program" [6].

1.3.5 Phase III-A: Roll Rate Feedback for Fishhook Timing

The Phase II testing uncovered weaknesses in some of the maneuvers used. Phase III research focused on resolving maneuver problems and improving selected test maneuvers.

The utilization of a programmable steering controller for the Phase II testing permitted very precisely controlled, highly repeatable, handwheel steering inputs. For the fishhook maneuver, having this precise steering control led to the question of exactly when to perform the handwheel steering reversal so as to maximize a vehicle's chances of two-wheel lift/rollover. To achieve two-wheel lift at the lowest possible speed and lateral acceleration, the authors thought that the steering reversal should start at the instant when the vehicle roll angle due to the initial steer had attained its maximum value. For the Phase II testing, the steering reversal timing was determined based on the vehicle's roll natural frequency value at 50 mph.

Natural frequency determination was not successful during Phase II; most test vehicle responses were very flat. Consequently, maneuver severity may have been adversely affected. Furthermore, the roll natural frequency of a vehicle has been shown to change as a function of vehicle speed. This is a problem because fishhook tests performed by NHTSA begin with a low vehicle speed that is then iteratively increased until two-wheel lift, or some abort criteria, occurs. During the course of Phase II testing, Ed Heitzman (co-developer of the Programmable Steering Controller used for the Phase II testing) suggested an alternative method to produce more desirable steering reversal timing. His idea was to initiate the reversal at the instant the vehicle roll rate first goes to zero after the initial steer. Since roll rate is the derivative of roll angle, this should guarantee having a maximum roll angle at the onset of the steering reversal.

Phase III-A of the Light Vehicle Rollover Research program implemented this technique for determining when to perform the handwheel steering reversal. Three objectives were established for the Phase III-A research:

1. Purchase/develop the hardware, software and procedures needed for the programmable steering controller to start the steering reversal at the instant when the vehicle roll rate first goes to zero after the initial steer.

2. Assess the repeatability of the automated "steering reversal at maximum roll angle" technique.

3. Compare vehicle response severity of automated steering reversals at maximum roll angle to that induced by the Phase II Fishhooks to determine whether a more severe maneuver had, in fact, been achieved.

Testing for Phase III-A of NHTSA's Vehicle Rollover Research program was performed from March through July of 2000. The results of the Phase III-A research are documented in the NHTSA Technical Report "Automated Steering Reversals Performed at Maximum Roll Angle in the Fishhook Maneuver – Phase III-A of NHTSA's Light Vehicle Rollover Research Program" [7].

1.3.6 Phase III-B: Automation of Pulse Braking

Another issue discovered during the analyses of the Phase II testing was the inability of test drivers to generate braking pulses of sufficient repeatability (for the J-Turn with Pulse Braking maneuver) so as to not have noticeable run-to-run differences for repeated runs that were nominally the same. The Phase I-A testing indicated that drivers could generate sufficiently repeatable pulses. What was initially overlooked was that the timing of the brake pulse, with respect to the time of initiation of the handwheel input used for the J-Turn maneuver, had a pronounced effect on the vehicle response. The authors anticipated that the use of roll rate control feedback to determine the timing of the brake pulse could maximize the severity of the vehicle's response.

Phase III-B of the Light Vehicle Rollover Research program upgraded NHTSA's programmable steering controller to facilitate automated braking. The updated controller could be programmed to initiate pulse braking at the instant when the vehicle roll rate first goes to zero after the initial steer. (Again, since roll rate is the derivative of roll angle, this should guarantee having a maximum roll angle at the onset of pulse braking.) Three objectives were established for the Phase III-B research:

1. Purchase/develop the hardware, software, and procedures needed to update NHTSA's programmable steering controller. The updated controller was to have the capability of applying pulse brake inputs at the instant the vehicle roll rate first goes to zero after the initial steer.

2. Assess the repeatability of this programmable braking and steering controller.

3. Better determine the effects of brake pulse magnitude, brake pulse width, and brake pulse initiation time on the severity of the vehicle response. Determine whether initiating pulse braking at the instant of maximum roll angle increased the severity of the resulting maneuver.

Testing for Phase III-B of NHTSA's Vehicle Rollover Research program was performed from July through September of 2000. The results of the Phase III-B research are documented in the NHTSA Technical Report "Automated Pulse Braking in the J-Turn Maneuver – Phase III-B of NHTSA's Light Vehicle Rollover Research Program" [8].

1.4 Consumer Information on Rollover Resistance

Partially as a result of the Phase I and II research, NHTSA instituted a consumer information program on rollover resistance. In a June 1, 2000 Federal register notice [9], NHTSA proposed to include consumer information star ratings for rollover resistance of passenger cars and light trucks as part of its New Car Assessment Program (NCAP). NCAP has provided comparative consumer information on vehicle performance in frontal and side impact crashes for many years. NHTSA proposed a rating system based on the Static Stability Factor (SSF). SSF is the ratio of one half the vehicle's average track width divided by its center of gravity height. SSF was chosen over vehicle maneuver tests because it represents the first order factors that determine vehicle rollover resistance. Other reasons for selecting the SSF measure were: driving maneuver test results are greatly influenced by SSF; the SSF is highly correlated with actual crash statistics; it can be measured accurately and explained to consumers; and changes in vehicle design to improve SSF are unlikely to degrade other safety attributes.

In general, the response of the automotive manufacturers to the June 2000 notice were that star ratings based on SSF were too simplistic because they did not include the effects of suspension deflections, tire traction, and electronic stability control and that the influence of vehicle factors on rollover risk was so slight that vehicles should not be rated for rollover resistance. The Consumers Union commented that although SSF is a useful predictor of tripped rollover, it should be used in conjunction with a dynamic stability test using vehicle maneuvers to better predict the risk of untripped rollovers.

In the fiscal year 2001 Department of Transportation Appropriation Act, Congress allowed NHTSA to move forward with providing consumer information star ratings based on SSF for rollover resistance. However, Congress also directed NHTSA to fund a National Academy of Sciences' study on vehicle rollover ratings. The study was to assess "whether the static stability factor is a scientifically valid measurement that presents practical, useful information to the public including a comparison of the static stability factor test versus a test with rollover metrics based on dynamic driving conditions that may induce rollover events."

Following the receipt and consideration of comments from interested parties, in a January 12, 2001 notice in the Federal register [10], NHTSA announced that it would proceed with the consumer information star ratings on rollover resistance based on SSF. Rollover resistance star ratings have been added to the frontal and side crash star ratings that were previously provided by the New Car Assessment Program (see www.nhtsa.dot.gov/NCAP/ for ratings, vehicle details and explanatory information).

1.5 Rollover Resistance Requirements of the TREAD Act

Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" reflects the desire of Congress, Consumers Union, and other parties to supplement SSF with a dynamic stability test using vehicle maneuvers. It directed NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into the New Car Assessment Program by November 1, 2002. The research described in this report has been performed as part of NHTSA's effort to fulfill the requirements of the TREAD Act.

1.6 Structure of This Report

Chapter 1 has briefly discussed the rollover safety problem, presented the relationship between the current research and past NHTSA rollover research, and talked about the mandate of the TREAD Act. Chapter 2 explains the objectives and test matrix for the work presented in this report, and discusses some important points about the related test and analysis procedures. Chapter 3 describes the test vehicles, discusses the various vehicle configurations used for this research, shows inertial parameters for each of the vehicle configurations, and discusses the tires that were used. Chapter 4 describes the instrumentation and data acquisition systems that were installed in each test vehicle.

Chapter 5 discusses one of the five Phase IV Characterization Maneuvers, the Slowly Increasing Steer maneuver. This chapter includes a maneuver description, presentation of input and output repeatability, and maneuver results. It is concluded with a discussion and conclusion. For the sake of brevity, results from the other Characterization Maneuvers will be discussed in a later report.

Chapter 6 describes the methodology that was used for determining NHTSA J-Turn, Fishhook 1a, and Fishhook 1b handwheel steering angles during the Phase IV testing.

Chapters 7 through 10 discuss dynamic rollover propensity testing for maneuvers J-Turn and Fishhook maneuvers. The programmable steering machine was used for these tests. Each chapter includes a maneuver description, presentation of input and output repeatability, and maneuver results. Maneuver results include discussions of two-wheel lift, tire debeads, and/or rim-to-pavement contact. Each chapter concludes with a maneuver assessment section.

Chapters 11 through 13 discuss driver-based, path-following, double lane change dynamic rollover propensity maneuvers. The programmable steering machine was **not** used for these tests. Again, a maneuver description and maneuver results are contained in each chapter. Because these maneuvers required steering by test drivers, these chapters emphasize input and output repeatability. Each chapter is concluded with a maneuver assessment section.

Chapter 14 presents the open-loop pseudo-double lane changes performed in Phase IV. The steering inputs used to define these dynamic rollover propensity maneuvers were based on those observed during driver-based, path-following testing but the actual steering inputs were generated by the programmable steering machine. This chapter includes a maneuver description, presentation of repeatability, and maneuver results. The chapter concludes with a maneuver assessment section.

The final portion of this report (Chapters 15 and 16) wrap-up this research. Chapter 15 compares the two-wheel lifts that observed across the different dynamic rollover propensity maneuvers, a fishhook dwell time comparison, and a discussion that relates the steering input by drivers during path-following tests to those used in the automated dynamic rollover propensity maneuvers. Chapter 16 features the overall discussion and conclusions from this research.

2.0 OBJECTIVES

2.1 Structure of the 2001 - 02 Rollover Research Program

As previously stated, this research has been performed as part of NHTSA's effort to fulfill the requirements of Section 12 of the TREAD Act. In response to the TREAD Act, NHTSA either has or will perform Phases IV, V, and VI of its Light Vehicle Rollover Research program. These phases are briefly described below:

2.1.1 Phase IV: Maneuver Selection and Procedure Development

The Phase IV testing was performed during the spring through fall of 2001. This phase was another exploratory study performed to examine a broad range of maneuvers that might induce on-road, untripped rollover. In many ways, this phase was a conceptual equivalent of Phase I-A, however some different maneuvers were studied and more sophisticated testing techniques were used. The work performed for this phase is explained in Section 2.2. In brief, five Vehicle Characterization and eight Rollover Resistance maneuvers were studied. Each maneuver studied was either discarded or retained for subsequent program phases.

The results of the Phase IV research are documented in this report.

2.1.2 Phase V: Maneuver and Procedure Finalization

Phase V will focus on resolving a number dynamic rollover testing issues. In many ways, Phase V will be a conceptual equivalent of Phase I-B research. Using the reduced set of maneuvers output from Phase IV, Phase V research will endeavor to:

1. Finalize the maneuvers and procedures to be used during Phase VI of the Light Vehicle Research program.

2. Determine how the installation of different outriggers may affect vehicle performance in dynamic rollover rating maneuvers.

3. Develop an understanding of the effects of performing dynamic rollover rating maneuvers on different test surfaces.

4. Develop an understanding of the effects of temperature on the outcomes of dynamic rollover rating maneuvers.

5. Quantify two-wheel lift with direct measurement, rather than review of test video data.

Testing for this phase will be performed during the winter of 2001 through the spring of 2002. The results of the Phase V research will be documented in a future NHTSA Technical Report.

2.1.3 Phase VI: Fleet Characterization

Phase VI will focus on determining the rollover resistance of a substantial number of vehicles. In many ways, Phase VI will be a conceptual equivalent to previous Phase II research. Testing for this phase will be performed during the spring through fall of 2002. The objectives of Phase VI of the Light Vehicle Rollover Research program will be:

1. To experimentally determine the rollover resistance of a broad range of light vehicle classes and, within classes, vehicle sizes using the test maneuvers and procedures developed during Phases IV and V of the Light Vehicle Rollover Research program.

2. To use the results from this testing to assist in the development of a dynamic rollover resistance rating test that can be incorporated into NCAP (as required by the TREAD Act).

The results of the Phase VI research will be documented in a future NHTSA Technical Report.

2.2 Work Performed for Phase IV of the Rollover Research Program

As stated above, Phase IV was another exploratory study of many possible test track maneuvers to quantify on-road, untripped, rollover propensity. The objective of this phase was to select a limited number of maneuvers to characterize a vehicle's rollover resistance. This study examined a broad range of maneuvers that might induce on-road, untripped rollover. Five Characterization and eight Rollover Resistance maneuvers were studied. Each Rollover Resistance maneuver studied was either discarded or retained for subsequent program phases. Each Rollover Resistance maneuver was evaluated based upon the following evaluation factors:

1. Their objectivity and repeatability, i.e., whether they could be performed objectively with, for the same vehicle, repeatable results.

2. Their performability i.e., how difficult each maneuver was to objectively perform while obtaining repeatable results, how well developed the test procedures for each maneuver were, and whether the test procedure included adequate means for adapting to differing vehicle characteristics.

3. Their discriminatory capability, i.e., whether they demonstrated poorer performance for vehicles that have less resistance to rollover. Although of obvious importance, a maneuver's ability to discriminate between different levels of vehicle handling was not considered.

4. Their appearance of reality, i.e., whether they might be performed by actual drivers while driving (particularly in emergencies). Appearance of reality was less important than the other three evaluation factors because we are interested in anything that the vehicle is capable of doing. What we desire are "worst case" maneuvers, but ones that drivers can perform.

For each of the above evaluation factors, each rollover resistance maneuver received an adjectival rating ranging from Excellent to Very Bad. While the authors have tried to objectively catalog the merits and problems of each maneuver, these ratings are subjective. Adjectival ratings were assigned as follows:

> **Excellent.** In the evaluated aspect, this maneuver is the best (or tied for best) of all of the rollover resistance maneuvers studied. In this aspect, this maneuver is adequate for use in a Government rollover resistance rating system.
>
> **Good.** In the evaluated aspect, this maneuver is substantially better than adequate but not the best of the rollover resistance maneuvers studied. In this aspect, this maneuver is adequate for use in a Government rollover resistance rating system.
>
> **Satisfactory.** In the evaluated aspect, this maneuver is adequate for use in a Government rollover resistance rating system.
>
> **Bad.** This maneuver has a substantial problem for this evaluation factor. In the evaluated aspect, this maneuver is **not** adequate for use in a Government rollover resistance rating system.
>
> **Very Bad.** This maneuver has multiple substantial problems for this evaluation factor. In the evaluated aspect, this maneuver is **not** adequate for use in a Government rollover resistance rating system.

2.2.1 Vehicles Tested

Four sport utility vehicles were tested in Phase IV. Three of these vehicles were purchased new for this research while one (the 1999 Mercedes ML320) was slightly used, having seen some prior usage as a test vehicle. Two of these vehicles (the 2001 Toyota 4Runner and 1999 Mercedes ML320) were equipped with electronic stability control systems as standard original equipment. For the purposes of the Phase IV test matrix (presented in Table 2.1), each vehicle with enabled stability control was treated as a different vehicle from that with disabled stability control. The six Phase IV test vehicles were:

1. 2001 Chevrolet Blazer.
2. 2001 Ford Escape[1].
3. 1999 Mercedes ML320 with disabled stability control.
4. 1999 Mercedes ML320 with enabled stability control.
5. 2001 Toyota 4Runner with disabled stability control.
6. 2001 Toyota 4Runner with enabled stability control.

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[1] The Automotive News Truck Market classifications classify this vehicle as a Sport Wagon instead of a Sport Utility Vehicle.)

Additional information about these test vehicles is contained in Chapter 3 of this report.

Each test vehicle was tested in three configurations. Configuration descriptions are as follows:

> **Nominal Load.** The Nominal Load consisted of the driver, instrumentation, and outriggers.
>
> **Reduced Rollover Resistance.** In addition to the Nominal Load, sufficient weight was placed on the roof to reduce the vehicle's SSF by 0.05. The weight on the roof was positioned so that the longitudinal/lateral position of the center of gravity did not change. Additional details are contained in Chapter 3 of this report.
>
> **Modified Handling.** Depending on the vehicle, this condition was achieved in one of two ways. The first technique was to load a vehicle to its rear Gross Axle Weight Rating (GAWR) while simultaneously achieving the Gross Vehicle Weight Rating (GVWR). The load was positioned so that it did not affect the center of gravity height or lateral position in the vehicle, only its longitudinal location. For the second technique, different tires/wheels approved/sold as OEM equipment for a particular vehicle were installed. Additional details are contained in Chapter 3 of this report.

The Reduced Rollover Resistance configuration was used as a maneuver sensitivity check. For many sport utility vehicles, a 0.05 reduction in SSF equates to approximately a one star reduction in that vehicle's rollover resistance rating[2]. NHTSA believes that a one star reduction in the rollover resistance rating should make a vehicle substantially easier to rollover. Maneuvers with good discriminatory capability should measure substantially worse performance for the Reduced Rollover Resistance configuration than for the Nominal Load configuration.

The Modified Handling configuration was used to examine how changes that affect a vehicle's handling affect its dynamic rollover propensity. Unlike the Reduced Rollover Resistance configuration, there was no prior expectation that the Modified Handling configuration vehicles would perform either better or worse than the Nominal Load vehicle configurations.

2.2.2 Maneuvers Examined

Prior to the initiation of the Phase IV research, NHTSA met with the Alliance of Automobile Manufacturers, Ford Motor Company, Nissan Motors, Toyota Motor Company, Consumers Union of the United States, MTS Systems Corporation, and other interested parties to gather information on possible approaches for dynamic rollover tests. NHTSA also corresponded with the University of Michigan Transportation Research Institute and Heitz Automotive, Inc. These parties made specific suggestions about approaches to dynamic testing of vehicle rollover

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[2] An SSF reduction of 0.05 does not always correspond to a one star rating reduction. The minimum span of a star rating is 1.12 minus 1.03 (from the highest one star to the highest two star), nearly twice that value. Also noteworthy is that a larger reduction in SSF is necessary to achieve a one star rating reduction for vehicles, such as passenger cars, that have higher SSFs.

resistance. Based on these suggestions plus NHTSA's experience in this area, the Phase IV test matrix was developed.

In a manner similar to Phase II, the Phase IV maneuvers can be divided into two types, the Characterization maneuvers and the Rollover Resistance maneuvers. Characterization maneuvers were used to characterize the transient dynamics, the maximum attainable lateral acceleration, and the responsiveness of the vehicle. Rollover Resistance maneuvers endeavored to reveal situations for which two-wheel lift occurred. Detailed descriptions of each maneuver are contained in later chapters of this report.

2.2.2.1 Characterization Maneuvers

Phase IV had five Characterization maneuvers. Four of these were also used during the Phase II testing. However, for Phase IV, an additional Characterization maneuver, the J-Turn Response Time Test, has been added to the matrix. Brief Characterization maneuver descriptions are as follows:

> **PULSE STEER.** This maneuver consisted of a short steering pulse while traveling at constant speed. It was used to characterize the transient dynamics of the vehicle.
>
> **SINUSOIDAL SWEEP STEER.** This maneuver consisted of sinusoidal steering of increasing frequency while traveling at a constant speed. It was also used to characterize the transient dynamics of the vehicle.
>
> **SLOWLY INCREASING STEER.** This maneuver consisted of slowly turning the steering wheel while maintaining a constant speed (if possible). It was used to determine the maximum lateral acceleration and understeer gradient of the vehicle and to define steering angles for certain Rollover Resistance maneuvers used in Phase IV.
>
> **SLOWLY INCREASING SPEED.** This maneuver consisted of turning the steering wheel by a fixed amount and then holding it steady while increasing vehicle speed. It was used to determine the maximum lateral acceleration and understeer gradient of the vehicle. There were some problems with the Phase II version of this maneuver, and an attempt was made to resolve them during the current research.
>
> **J-TURN RESPONSE TIME TESTS.** These maneuvers consisted of low and moderate severity J-Turns, performed both with a straight lead-in and with a 0.3 g constant lateral acceleration lead-in. They were used to determine vehicle response times.

Complete details of the Slowly Increasing Steer maneuver are in Chapter 5. Results from the other Characterization maneuvers will be discussed in a later report.

2.2.2.2 Rollover Resistance Maneuvers

Phase IV included one J-Turn, three Fishhooks, and four double lane changes. Brief Rollover Resistance maneuver descriptions are as follows:

> **NHTSA J-TURN.** This was a high severity J-Turn. It was performed using the same protocol as were the Phase II J-Turns with except that the maximum handwheel steering angle magnitude was equal to a multiplier times the handwheel angle at which 0.3 g lateral acceleration was attained during the Slowly Increasing Steer test.
>
> **NHTSA FISHHOOK 1A.** This maneuver is also known as the FIXED TIMING FISHHOOK. It was an improved version of the Phase II Fishhook 1 Maneuver. Phase IV improvements are listed below. Like that used in Phase II, the programmed handwheel dwell times remained at 250 ms for each vehicle.
>
> - All handwheel steering rates were fixed at 720 degrees per second, not based on roll angle natural frequency.
> - The maximum initial steer handwheel angle magnitude was equal to a multiplier (not the same multiplier as for the J-Turn) times the handwheel angle at which 0.3 g lateral acceleration was attained during the Slowly Increasing Steer test.
> - The countersteer magnitude was equivalent to the maximum initial steer angle rather than 600 degrees. This change was made because the authors believe the large countersteer used during Phase II was not required for maximum maneuver severity, and contributed to excessive tire wear.
>
> **NHTSA FISHHOOK 1B.** This maneuver is also known as the ROLL RATE FEEDBACK FISHHOOK. It is another improved version of the Phase II Fishhook 1 Maneuver. Fishhook 1a improvements 1 through 3 were also applied to Fishhook 1b. Additionally, use of roll rate feedback (developed during Phase III) was used to determine handwheel reversal timing.
>
> **NISSAN FISHHOOK.** This maneuver used a procedure developed by Nissan to determine handwheel reversal timing. As was the case for Fishhook 1b, the goal was to make the reversal a vehicle-dependent parameter. However, for the Nissan Fishhook, an iterative procedure was used to determine handwheel dwell time in lieu of roll rate feedback.

Phase IV included four double lane change maneuvers. Three differed from those used during the Phase I-A testing[3]. The double lane change maneuver codes and descriptions are as follows:

[3] No driver-based closed-loop double lane changes have been performed by NHTSA Research and Development since Phase I-A of the Rollover Research Program.

PATH CORRECTED LIMIT LANE CHANGE (PCL LC). This maneuver used a procedure developed by Ford Motor Company that endeavors to predict a vehicle's limit performance. Ford has developed a method for analyzing the data that removes driver effects (i.e., making the results independent of the driver's strategy and control inputs). Testing for this maneuver included the use of three drivers for one vehicle/configuration so that this independence could be verified.

ISO 3888 PART 2 DOUBLE LANE CHANGE. Although many variants of this maneuver exist (e.g., the "Moose Test"), Phase IV tests used the course layout procedure defined in ISO 3888, Part 2. Inclusion of this particular procedure was recommended to NHTSA by the Alliance of Automobile Manufacturers. Since this was a driver-based closed-loop test, duplicate tests were performed by three drivers.

CONSUMERS UNION SHORT COURSE DOUBLE LANE CHANGE. This maneuver was developed by Consumers Union to examine a vehicle's emergency handling capabilities. Since this was a driver-based closed-loop test, duplicate tests were performed by three drivers.

OPEN-LOOP PSEUDO-DOUBLE LANE CHANGE. The goal of this maneuver was to have the appearance of reality of a double lane change and the repeatability of a steering controller test. For this maneuver, the handwheel steering input of a "typical" double lane change was experimentally determined. The steering controller was then programmed to repeatably generate this steering input.

2.2.3 Phase IV Test Matrix

Table 2.1 presents the Phase IV test matrix. The matrix indicates which test maneuvers were examined for each test vehicle and vehicle configuration.

Due to the inability of the steering machine to perform high frequency sine sweeps, Sinusoidal Sweep testing was not performed for a number of test vehicles, at least for some configurations. No Sinusoidal Sweeps were performed with the Mercedes ML320, the Toyota 4Runner in the Reduced Rollover Resistance configuration, and the 4Runner with enabled VSC in the Nominal Load configuration.

Mercedes ML320 and Toyota 4Runner J-Turn Response Time tests were not performed with disabled stability control. No intervention was detected during tests performed with enabled stability control, so these test were not deemed necessary. In retrospect, this logic could have been applied to Pulse Steer testing as well.

The Nissan Fishhook was performed only with the Chevrolet Blazer and Ford Escape. The authors believe that testing these two vehicles gave them a full understanding of this maneuver; testing additional vehicles was unnecessary.

The Open-Loop Pseudo Double Lane Change was performed only with the Chevrolet Blazer and Toyota 4Runner. The authors believe that testing these two vehicles gave them a full understanding of this maneuver; testing additional vehicles was unnecessary.

The Consumers Union Short Course Double Lane Change was performed only for vehicles in the Nominal Load configuration. Insufficient time was available to test each vehicle in additional configurations. Also, the authors believe that performing this maneuver for additional vehicle configurations would not have substantially improved their understanding of this maneuver.

Table 2.1. The Phase IV Test Matrix**.**

Maneuver	**2001 Chevrolet Blazer**			**2001 Ford Escape**			**1999 Mercedes ML320**						**2001 Toyota 4Runner**					
							Disabled ESC			**Enabled ESC**			**Disabled ESC**			**Enabled ESC**		
	VC1	VC2	VC3	VC1	VC2	VC3	VC1	VC2	VC3	VC1	VC2	VC3	VC1	VC2	VC3	VC1	VC2	VC3
Pulse Steer	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sinusoidal Sweep	X	X	X	X	X	X												
Slowly Increasing Steer	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Slowly Increasing Speed	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
J-Turn Response Time	X	X	X	X	X	X				X	X	X				X	X	X
NHTSA J-Turn	X	X		X	X		X	X		X	X		X	X		X	X	
NHTSA Fishhook 1a	X	X		X	X		X	X		X	X		X	X		X	X	
NHTSA Fishhook 1b	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nissan Fishhook	X			X														
Ford PCL LC	X			X			X			X			X			X		
ISO 3888 Part 2	X	X		X	X		X	X		X	X		X	X		X	X	
CU Short Course	X			X			X			X			X			X		
Open-Loop Pseudo DLC	X												X			X		

Note: VC = Vehicle Configuration

VC1 = Nominal Load
VC2 = Reduced Rollover Resistance
VC3 = Modified Handling

2.3 Test Surface

All Phase IV tests were performed on the Transportation Research Center, Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The VDA is an 1800 by 1200 foot flat paved surface with a one percent longitudinal grade intended to provide drainage. Turn-around loops are provided on each end to facilitate high speed entry onto the VDA. The surface was paved with asphalt of a mix representative of that used to construct many Ohio highways. All Phase IV tests were performed on dry pavement.

The VDA's peak and sliding coefficients of friction were generally monitored twice per month, weather-permitting, using American Society for Testing and Materials (ASTM) procedures. The peak coefficient was determined by using ASTM procedure E1337 with an E1136 tire [11, 12]. Sliding coefficients were determined with ASTM procedure E274 with an E501 tire [13, 14]. Table 2.2 summaries the results of these tests for 2001.

Phase IV tests were performed from April 19 through November 16, 2001, and on February 7, 2002[4]. The VDA's peak coefficient of friction ranged from 0.94 to 0.98 during the testing period. The slide coefficient varied slightly more, ranging from 0.81 to 0.88. The January 3, 2002 measurements were taken closest in time to the tests performed on February 7.

As could be inferred from the test dates, testing was performed with a fairly broad range of ambient temperatures. The lowest ambient testing temperature was approximately 47° F, recorded prior to a series of tests performed on February 7th. The highest ambient testing temperature was approximately 88° F, recorded prior to a series of tests performed on July 24th.

[4] The steering used during one open-loop double lane change test series was not correct. Tests performed on February 7, 2002 used the correct inputs.

Table 2.2. Peak and Slide Coefficients of Friction During Calendar Year 2001 for the TRC VDA.

Date	Coefficient Of Friction	
	Peak	Sliding
01.11.2001	N/A	N/A
02.08.2001	N/A	N/A
03.08.2001	N/A	N/A
03.19.2001	0.95	N/A
04.16.2001	0.92	0.80
04.30.2001	0.94	0.81
05.14.2001	0.94	0.83
06.04.2001	N/A	0.84
06.28.2001	0.94	0.81
07.09.2001	0.95	0.83
08.08.2001	0.96	0.81
08.24.2001	0.94	N/A
09.11.2001	0.98	0.85
09.28.2001	0.95	0.88
10.16.2001	0.94	0.88
11.05.2001	0.95	0.87
11.26.2001	N/A	N/A
12.11.2001	0.95	N/A
01.03.2002	0.95	0.85
03.29.2002	0.96	0.85

3.0 TEST VEHICLES AND CONFIGURATIONS

3.1 Vehicle Selection Rationale

The Phase IV vehicle fleet was comprised of four sport utility vehicles (SUVs). Three vehicles were purchased as new 2001 models. One was a 1999 model year vehicle, purchased new by NHTSA in 1999. Only SUVs were chosen because crash data have shown they are involved in the greatest percentage of light vehicle rollovers per single vehicle crash (as discussed in Chapter 1). The SUVs chosen cover the entire range of SUV Static Stability Factors with SSFs ranging from 1.025 to 1.232. Their Rollover Resistance Star Ratings range from one to three stars. If the maneuvers intended to evaluate light vehicle dynamic rollover propensity are not capable of discriminating between the Phase IV vehicles, it is unlikely that they will be able to discriminate between good and poor rollover resistance for the entire set of light vehicles.

The Phase IV vehicles were chosen on the basis of certain desirable specifications, statistical significance, and/or characteristics. The vehicles and the rationale for their inclusion are as follows:

- **2001 Chevrolet Blazer LS 4x2 (SSF = 1.025).** The Blazer, and its sister the GMC Jimmy 4x2, have historically had high volume sales numbers. These vehicles were the only 2001 models to receive one-star rollover resistance ratings. Including the Blazer in Phase IV was important, as it provided an opportunity to compare the rollover resistance predicted by the vehicle's low SSF to the dynamic rollover propensity observed during on-road, untripped, rollover maneuvers.

- **2001 Toyota 4Runner SR5 4x4 (SSF = 1.098).** An important feature of the 4Runner was its Vehicle Skid Control (VSC) system. This electronic stability control system was not available on the 2000 model year 4Runner but was standard equipment for 2001. At the time of vehicle procurement, very few SUVs were available with stability control. NHTSA had briefly examined the influence of stability control on the dynamic rollover propensity of a 2000 Lexus LX470[1] leased from Toyota and found its intervention to be "more aggressive" than that associated with its peer vehicle, a 1999 Mercedes ML320. Since the LX470 was not available for the anticipated duration of Phase IV testing, substitution of another vehicle equipped with an aggressive stability control system was desired. In its correspondence with NHTSA, Toyota explained that the VSC control algorithms (including the intervention aggressivity) of the LX470 and 4Runner were very similar. Due to the significantly lower cost of the 2001 4Runner, when compared to that of the 2001 LX470, a 4Runner was purchased for use in Phase IV.

[1] A presentation reporting some of this research is available at http://www-nrd.nhtsa.dot.gov/pdf/nrd-01/SAE/Forken1.PDF

No provision for disabling the 4Runner's VSC is available to the driver (although Toyota instructed the authors how to disable it for testing purposes). Based on SSF, this vehicle has a two-star rollover resistance rating.

- **1999 Mercedes-Benz ML320 4x4 (SSF = 1.123).** Like the Toyota 4Runner, the ML320 has a two-star rollover resistance rating. The ML320 possessed the lowest sales volume of the Phase IV test fleet. However, the decision to include the ML320 was not based on sales data. The 1999 ML320 and ML430 were the first production SUVs available with electronic stability control (called Electronic Stability Program, or ESP, for these vehicles). These systems were not available for 1998 model year vehicles, but were installed as standard equipment in 1999.

  The electronic stability control system of the 1999 ML320 differs from that offered by Toyota in a number of ways. First, ESP can be deactivated by the driver via a button located on the center console. Second, the contribution of the rear brakes during ESP intervention is much less. The authors deemed the "less aggressive" nature of this intervention to be a valuable characteristic to examine during Phase IV.

  It should be noted that the stability control system of the Mercedes ML320 and ML430 was revised for the 2001 model year. The stability control intervention observed during Phase IV tests performed with the 1999 ML320 may not necessarily be representative of that employed by the revised version. The extent to which the revised system may have changed the test results produced with the 1999 ML320 is unknown.

- **2001 Ford Escape XLS 4x4 (SSF = 1.232).** The Ford Escape, and its sister the Mazda Tribute 4x4, were introduced in late 2000 as 2001 model year vehicles. As such, sales volume at the time of vehicle procurement was not particularly meaningful. Inclusion of the Escape was important because at that time, it was the only SUV to receive a three-star rollover resistance rating. The vehicle's SSF value was the highest of the Phase IV test fleet, thus predicting the lowest rollover propensity of the group.

Table 3.1 provides several descriptive parameters for each Phase IV test vehicle. These parameters are not intended to be a comprehensive description of each vehicle, but to highlight certain features the authors deemed relevant to rollover propensity. Detailed wheel and tire information is contained in the "**Tires**" section of this chapter.

Table 3.1. Test Vehicle Descriptive Parameters.

Vehicle	Engine	Misc Features	Wheelbase (in)	Mean Track Width (in)	Test Weight Without Outriggers (lbs)	Steering Ratio (deg/deg)	SSF Rollover Rating
2001 Blazer	4.3L V6	4-spd auto, 4-dr, 2WD, solid rear axle	107.1	54.6	3998	18.5	★
2001 4Runner	3.4L V6	VSC, 4-spd auto, 4-dr, 4WD, solid rear axle	105.3	59.5	4239	21.1	★★
1999 ML320	3.2L V6	ESP, 5-spd auto, 4-dr, 4WD, glass sunroof, independent rear suspension	110.9	60.1	4669	19.7	★★
2001 Escape	3.0L V6	4-spd auto, 4-dr, 4WD, independent rear suspension	103.1	61.0	3504	17.3	★★★

Calculation of the steering ratios (provided in column seven of Table 3.1) required handwheel and road wheel angle data. Using increments of 90 degrees, the handwheel was turned clockwise from zero to 450 degrees, then back to zero. At each increment, the road wheel angles of both front wheels were measured with low coefficient of friction suspension alignment plates. The process was repeated with counterclockwise steering. Data was plotted to check for hysteresis. Linear regressions were performed for each wheel to assess statistical correlation. The R-squared coefficients were greater than 0.998 for each front wheel, for all vehicles. The absolute values of the two regression line slopes were averaged to yield a final, overall steering ratio for each vehicle. Accurate determination of the steering ratio was important, as these values were later used in understeer gradient calculations.

3.2 Tires

3.2.1 Description

All tires used in NHTSA's Phase IV research were new, and of the same make, model, size, and DOT specification of those installed on vehicles when purchased new. All tests were performed with the tires inflated to pressures recommended by each manufacturer on the vehicle identification placards. Table 3.2 presents tire information for each Phase IV vehicle. Tire makes, models, sizes, and DOT codes are provided. In Table 3.2, a tire described as "OEM" means that it was installed on the vehicle when received by VRTC from the dealer. "Optional" tires are available to the consumer as optional equipment or as part of a wheel/tire accessory package. In either case, these tires were approved by the vehicle manufactures, and should not be mistaken as aftermarket offerings. The inflation pressures given in Table 3.2 were those recommended by the vehicle manufacturers on the tire inflation placards.

Table 3.2. Phase IV Overall Tire Summary.

Vehicle	Description	Make	Model	Size	DOT	Inflation Pressure			
						Nominal		GVWR	
						Front	Rear	Front	Rear
2001 Blazer	OEM	Uniroyal	Laredo (TPC Spec 1128 MS)	P235/70R-15 102S	APM1	32	32	32	32
2001 4Runner	OEM	Bridgestone	Dueler H/T 689	P265/709R-16 111S	ELLJ	32	32	32	32
1999 ML320	OEM	Dunlop	Grandtrek T.G. 35	255/65R-16 109H	DB3X	32	32	32	39
	Optional	Dunlop	Grandtrek T.G. 35	275/55R-17 109H	DBVJ	32	32	32	39
2001 Escape	OEM	General	Grabber AW	P225/70R-15 100S	ACUU	30	30	30	30
	Optional	Firestone	Wilderness HT	P235/70R-16 104T	W208	30	30	30	30

3.2.2 Break-In Procedure

All tires were driven for 100 miles at 60 mph around a 7.5 mile oval track located at the Transportation Research Center, Inc. (TRC) in East Liberty, Ohio. Once mileage had been accumulated, the tires were dismounted and put into storage until used.

3.2.3 Mounting Technique

When mounted to the rims used for testing, no lubricant was used. If lubricant was used to mount the tire for the purposes of mileage accumulation, it was removed prior to being subjected to actual testing. Lubricant was not used due to uncertainty surrounding the three occurrences of tire debeading observed during the Phase II rollover research. To eliminate the possibility of tire lubricant contributing to this phenomenon, it was not used.

3.2.4 Frequency of Changes

To minimize the effects of tire wear on vehicle response and rollover propensity, Phase IV rollover research required frequent tire changes. One set of tires was used for the Pulse Steer, Sinusoidal Sweep, and Slowly Increasing Steer characterization maneuvers. A second set was used for the J-Turn Response Time and Slowly Increasing Speed characterization maneuvers. All other tests used one tire set per test condition and/or vehicle configuration (e.g., one set per J-Turn maneuver sequence, one set per Fishhook maneuver sequence, etc). For closed-loop tests using multiple drivers per vehicle, one tire set was used per driver.

3.2.5 Use of Inner Tubes

Fishhook maneuvers produced tire debeading during tests performed with two of the four Phase IV vehicles. The repeated occurrence of these debeads ultimately resulted in significant damage to the test surface (as shown in Figure 3.1), forcing the authors to investigate ways to prevent it. It was concluded that the easiest, most cost effective way to prevent debeads was the use of inner tubes designed for radial tires.

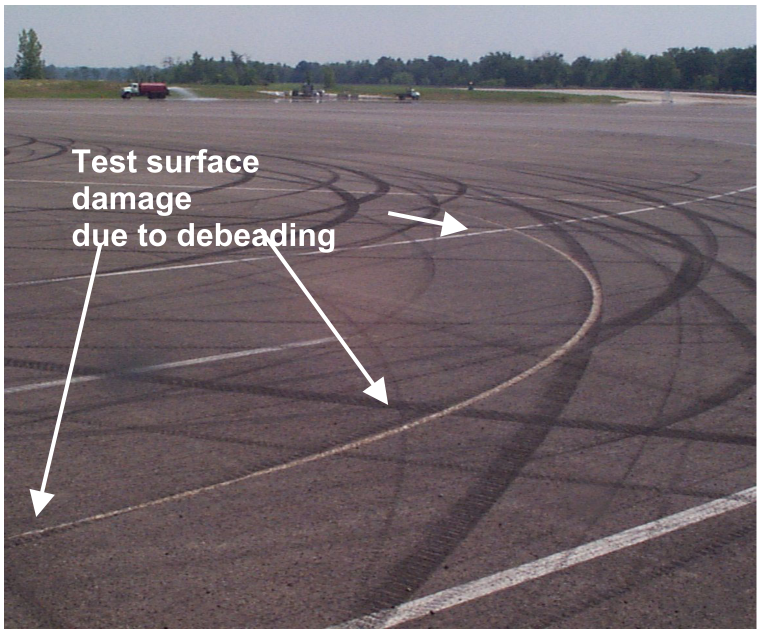

Figure 3.1. Pavement damage resulting from a left front tire debead during a Fishhook 1a test performed with the Ford Escape.

Since the repeated debeading began after many Phase IV tests had already been performed, some fishhooks were performed with inner tubes, while others were not. Furthermore, some tests were performed with inner tubes installed in the left and right front tires only, while others were performed with inner tubes installed in each of the four tires. The use of front tire inner tubes was a first attempt to control debeading. While this prevented the loss of air pressure associated with debeading at the front of the vehicle, loss of rear air pressure and rear rim-to-roadway contact was observed. It is for this reason that NHTSA now requires inner tubes for all fishhook tests performed at VRTC, one inner tube for each of the vehicle's four tires.

Table 3.3 summarizes when inner tubes were used, and for which vehicles. Since implementing the use of inner tubes for fishhook tests, pavement damage produced by rim-to-roadway contact has been dramatically reduced. Scraping of the rim is detectable, but not severe enough to require replacement of the rim or repair to the test surface. Pavement damage is virtually imperceptible.

Consumers Union Short Course tests were the only others for which inner tubes were used in Phase IV. Because this closed-loop double lane change has at least two severe steering reversals, the authors believed it was possible for a debead situation to occur. As such, inner tubes were included for all Consumers Union Short Course tests, regardless of driver or vehicle. Inner tubes were not used during Path Corrected Limit Lane Change or ISO 3888 Part 2 tests, as no debeads had occurred prior to the conduct of these maneuvers.

Inner tubes were not installed for any characterization maneuver or J-Turn test, regardless of vehicle.

Table 3.3. Phase IV Inner Tube Installation Summary.

Vehicle	Loading Condition	Characterization Maneuvers (All)	J-Turn	Fishhooks			Closed-Loop Double Lane Changes			Open-Loop Double Lane Changes	
				1a	1b	Nissan	PCLLC	ISO	CU	ISO	CU
2001 Chevrolet Blazer	Nominal	None	None	LF; RF	LF; RF	All	None	None	All	All	All
	Reduced Rollover Resistance			LF; RF	All						
	Modified Handling			N/A	All						
2001 Toyota 4Runner	Nominal	None	None	None	None	Tests not performed	None	None	All	All	All
	Reduced Rollover Resistance			None	None						
	Modified Handling			N/A	All						
1999 Mercedes ML320	Nominal	None	None	None	None w/ESP; LF, RF w/o ESP	Tests not performed	None	None	All	Tests not performed	
	Reduced Rollover Resistance			Tests not performed							
	Modified Handling			N/A	LF; RF						
2001 Ford Escape	Nominal	None	None	None	None	All	None	None	All	Tests not performed	
	Reduced Rollover Resistance			LF; RF	LF; RF						
	Modified Handling			N/A	None						

3.3 Installation of Outriggers

All tests performed in Phase IV used outriggers attached to the front and rear bumper attachment points via steel brackets. The outriggers were fabricated from 6061-T6 aluminum I-beams, boxed in with 0.25 inch aluminum flat plates. Each outrigger measured approximately 148 inches from the center of each caster wheel, and weighed approximately 78 lbs. Figure 3.2 shows the Mercedes ML320 equipped with VRTC's aluminum outriggers.

Figure 3.2. 1999 Mercedes ML320 with VRTC aluminum outriggers.

The bottom of each caster wheel was initially set to 12 inches from the ground. The caster assemblies were raised, however, if contact with the ground prevented at least two inches of simultaneous two-wheel lift from being observed. In Phase IV, the greatest distance from the caster wheel to the ground was 14 inches. With this setting, a maximum chassis roll angle was observed to be approximately 20 degrees.

To quantify the effect of outrigger installation on the vertical center of gravity (C.G.) location and mass moments of inertia, each vehicle was tested on the Vehicle Inertial Measurement Facility (VIMF) at SEA, Inc. The evaluation was comprised of two conditions: baseline (as delivered from the dealership), and baseline with VRTC's aluminum outriggers[2] in lieu of the front and rear bumpers. Table 3.4 summarizes these data. A simulated driver was positioned in the driver's seat during all VIMF tests performed at SEA, Inc.

For each vehicle, installation of VRTC's aluminum outriggers lowered the C.G. height while increasing each mass moment of inertia. Increases in pitch inertia ranged from 8.2 percent (4Runner) to 18.9 percent (Escape). Roll inertia increased 14.6 percent (ML320) to 21.4 percent (Escape). Yaw inertia increased 11.0 percent (4Runner) to 22.1 percent (Escape).

[2] The baseline and baseline with aluminum outrigger condition measurements of the Mercedes ML320 were performed with 52 lbs of ballast placed on the passenger-side front seat to simulate the weight of instrumentation. This ballast was not used during VIMF tests performed with the three other Phase IV vehicles. No baseline data was available without this ballast for the ML320.

Table 3.4. Influence of Aluminum Outriggers on Vertical C.G. and Mass Moments of Inertia.

Vehicle	Baseline				Baseline with Aluminum Outriggers							
	Vertical C.G. (in)	Pitch Inertia (ft-lb-sec^2)	Roll Inertia (ft-lb-sec^2)	Yaw Inertia (ft-lb-sec^2)	C.G. Height (in)		Pitch Inertia (ft-lb-sec^2)		Roll Inertia (ft-lb-sec^2)		Yaw Inertia (ft-lb-sec^2)	
					Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)
2001 Blazer	26.6	2273	429	2384	26.3	**-1.3**	2573	**13.2**	520	**21.2**	2765	**16.0**
2001 4Runner	27.1	2437	463	2544	26.7	**-1.2**	2638	**8.2**	540	**16.6**	2824	**11.0**
1999 ML320[1]	26.8	2464	589	2628	26.3	**-1.8**	2770	**12.4**	675	**14.6**	3014	**14.7**
2001 Escape	24.8	1855	430	2002	24.2	**-2.4**	2206	**18.9**	522	**21.4**	2446	**22.1**

[1]VIMF tests performed with 52 lbs ballast (simulated instrumentation) positioned on the passenger-side front seat for the Mercedes ML320 only.

3.4 Vehicle Load Configurations

Phase IV testing included three loading conditions: Nominal Load, Reduced Rollover Resistance, and Modified Handling. A description of each condition is provided below. In each condition, the vehicle was fully fueled.

3.4.1 Nominal Load

The Nominal Load condition consisted of the driver, instrumentation, and aluminum outriggers. To quantify the influence of the Nominal Load condition on the C.G. height and mass moments of inertia, each vehicle was tested on the VIMF at SEA, Inc. Results from tests performed in the Nominal Load condition were compared with those measured in the baseline condition. Table 3.5 summarizes these data.

For each vehicle, the Nominal Load condition lowered the C.G. height while increasing each mass moment of inertia. Increases in pitch inertia ranged from 8.0 percent (4Runner) to 18.8 percent (Escape). Roll inertia increased 21.2 percent (ML320) to 27.8 percent (Blazer). Yaw inertia increased 10.5 percent (4Runner) to 21.1 percent (Escape).

Table 3.5. Comparison of Baseline and Nominal Loading Conditions.

Vehicle	Baseline				Nominal Loading							
	Vertical C.G. (in)	Pitch Inertia (ft-lb-sec^2)	Roll Inertia (ft-lb-sec^2)	Yaw Inertia (ft-lb-sec^2)	C.G. Height (in)		Pitch Inertia (ft-lb-sec^2)		Roll Inertia (ft-lb-sec^2)		Yaw Inertia (ft-lb-sec^2)	
					Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)	Measured	Increase from Baseline (%)
2001 Blazer	26.6	2273	429	2384	26.1	**-2.1**	2608	**14.7**	548	**27.8**	2784	**16.8**
2001 4Runner	27.1	2437	463	2544	26.5	**-2.1**	2632	**8.0**	581	**25.5**	2812	**10.5**
1999 ML320[1]	26.8	2464	589	2628	25.6	**-4.3**	2900	**17.7**	714	**21.2**	3121	**18.8**
2001 Escape	24.8	1855	430	2002	24.1	**-2.7**	2204	**18.8**	533	**24.1**	2425	**21.1**

[1] VIMF tests performed with 52 lbs ballast (simulated instrumentation) positioned on the passenger-side front seat for the Mercedes ML320 only.

3.4.2 Reduced Rollover Resistance

In addition to the equipment used in the Nominal Load condition, the Reduced Rollover Resistance loading included roof-mounted ballast positioned such that the longitudinal C.G. location was not affected. The weight of the ballast was such that it reduced the vehicles' SSF by 0.05. Table 3.6 presents the SSFs of each vehicle in the Reduced Rollover Resistance configuration, the weight of the ballast required to achieve the SSF reduction, and the C.G. height change.

Table 3.6. Vehicle-Based Data Required For Reduced Rollover Resistance Roof Ballast Determination.

Vehicle	Track Width (in)	Baseline With Outriggers (no instrumentation)				Reduced Rollover Resistance (without instrumentation)				VIMF Results	
		Weight (lbs)	Roof Height (in)	C.G. Height (in)	SSF	Desired SSF	Desired C.G. Height (in)	Assumed Tire / Suspension Deflection (in)	Required Roof Ballast (lbs)	Required Roof Ballast (lbs)	Difference from Calculated (%)
2001 Blazer	54.6	4154	65.4	26.3	1.038	0.988	27.6	0.425	181	179	-0.9
2001 4Runner	59.5	4344	67.9	26.7	1.113	1.063	28.0	0.425	172	N/A	
1999 ML320	60.1	4838	70.0	26.3	1.143	1.093	27.5	0.425	175	N/A	
2001 Escape	61.0	3708	66.2	24.2	1.263	1.213	25.2	0.425	121	121	0.2

The weight required to achieve a 0.05 SSF reduction was determined in two ways: via computation and direct measurement. In the first method, ballast requirements for each vehicle were calculated by summing moments about the desired Reduced Rollover Resistance vertical center of gravity. Overall suspension and tire deflection resulting from installation of the ballast was taken to be 0.425 inches. The second method utilized the Chevrolet Blazer and Ford Escape only. Ballast was iteratively increased and/or positioned on the vehicle while on the VIMF at SEA, Inc. These tests validated the calculated ballast requirements for Chevrolet Blazer and Ford Escape; the actual and calculated values differed by less than one percent (Blazer weights differed by 0.9 percent, while Escape weights differed by 0.2 percent). Table 3.6 summarizes the calculated weight requirements for each of the four vehicles, and compares Blazer and Escape requirements to those measured at SEA.

Note that the data presented in Table 3.6 does not include the effects of instrumentation. Only two vehicles were measured on the VIMF with roof ballast. These tests were performed early in the test program, and the vehicles had not yet been instrumented. For this reason the most appropriate data to use in the aforementioned calculations was that of the baseline condition (the vehicles as received from the dealer), but with outriggers in lieu of bumper assemblies.

In addition to the change in C.G. height, the influence of roof-mounted ballast on the vehicles' mass moments of inertia was measured for the Blazer and Escape while at SEA. The results of these tests are provided in Table 3.7. Similar data is not available for the Mercedes ML320 or Toyota 4Runner. Roof-mounted ballast increased roll inertia by 11.5 percent for the Blazer and by 8.0 percent for the Escape. Because the ballast was positioned at the longitudinal C.G., its effect on pitch inertia was expected to be small. This expectation was correct; the Blazer and Escape pitch inertia increased 2.5 and 2.0 percent, respectively. Changes in yaw inertia were expected to be negligible. This was also indeed the result, as changes in Blazer and Escape yaw inertia were less than one percent. As with the data presented in Table 3.6, that shown in Table 3.7 does not include the effects of instrumentation.

Table 3.7. Influence of Roof-Mounted Ballast on Vehicle Mass Moments of Inertia.

Vehicle	Nominal (without instrumentation)			Reduced Rollover Resistance (without instrumentation)					
	Pitch Inertia (ft-lb-sec^2)	Roll Inertia (ft-lb-sec^2)	Yaw Inertia (ft-lb-sec^2)	Pitch Inertia (ft-lb-sec^2)	Increase from Nominal (%)	Roll Inertia (ft-lb-sec^2)	Increase from Nominal (%)	Yaw Inertia (ft-lb-sec^2)	Increase from Nominal (%)
2001 Blazer	2573	520	2765	2637	**2.5**	579	**11.5**	2766	**0.1**
2001 Escape	2206	522	2446	2250	**2.0**	563	**8.0**	2443	**-0.1**

The Reduced Rollover Resistance configuration was not intended to simulate a real-world loading condition, but rather to serve as a maneuver sensitivity check. The authors believed a maneuver that effectively evaluates rollover propensity should be able to discriminate between a vehicle in the Nominal Load configuration and that vehicle in the Reduced Rollover Resistance configuration. Figure 3.3 provides an example of roof-mounted ballast on the Toyota 4Runner.

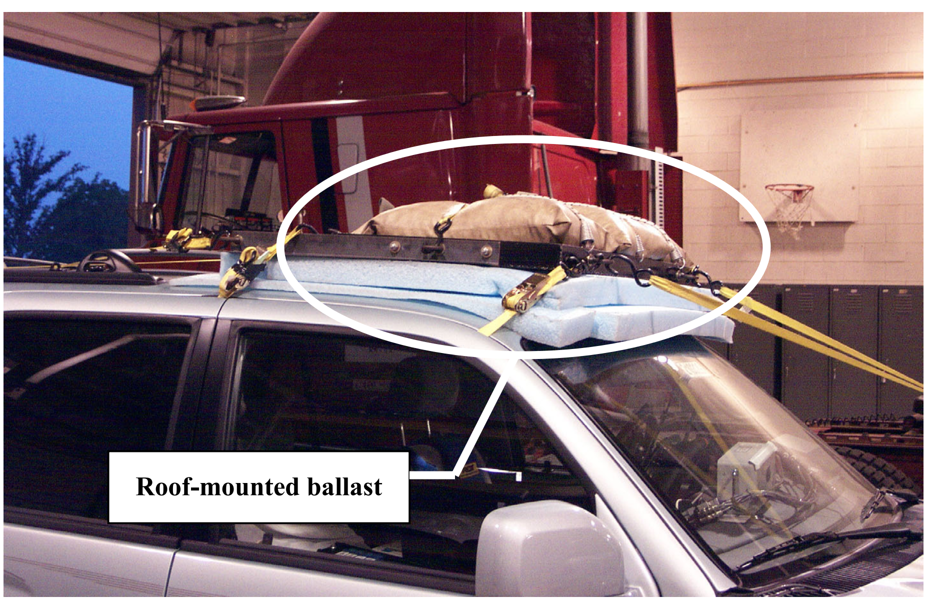

Figure 3.3. Roof-mounted ballast positioned on the 2001 Toyota 4Runner.

3.4.3 Modified Handling

The Modified Handling configurations were intended to affect vehicle handling using one of two methods: by installing larger wheel/tire combinations approved by the vehicle's manufacturer or by placing ballast in the cargo area behind the rear seat.

3.4.3.1 Optional Wheel/Tire Packages

The Ford Escape and Mercedes ML320 were the only Phase IV vehicles available with wheel/tire packages significantly different from those installed on the vehicle as it was received from the dealer. Table 3.8 summarizes these differences.

The Ford Escape was delivered with P225/70R-15 tires mounted to 15 x 6.5 inch aluminum alloy wheels. An optional wheel package was available on the Escape, comprised of P235/70R-16 tires mounted to 16 x 7 inch aluminum alloy wheels. This optional wheel package was used for the Escape's Modified Handling configuration. The outside diameter of the Escape's optional wheel/tire package was approximately 1.6 inches greater than that originally installed on the vehicle[3]. This raised the vertical C.G. slightly (approximately 0.8 inches), thus lowering the SSF.

The Mercedes ML320 was delivered with 255/65R-16 tires mounted to 16 x 8 inch aluminum alloy wheels. An optional wheel package was available on the ML320, comprised of 275/55R-17 tires mounted to 17 x 8.5 inch aluminum alloy wheels. This optional wheel package was used for the ML320's Modified Handling configuration. In the case of the Mercedes ML320, the diameter of the optional wheel/tire package was approximately 0.14 inches less than that originally installed on the vehicle[3]. Therefore, installation of this equipment had a negligible effect on the vertical C.G. and SSF of the ML320.

Although the Chevrolet Blazer was available with three optional tire/rim combinations, none were included in Phase IV. The first was an alternate tire option that simply increased the aspect ratio from 70 to 75 (from P235/70R-15 to P235/75R-15). The remaining two were more significant, but available only within "packages" containing additional equipment. The available "ZR2 Wide-Stance Sport Performance Package" included 31.0x10.5 R-15 tires, but also included chassis and suspension modifications. The "Xtreme" package included low-profile P235/60R-16 tires; however, it too included suspension modifications.

As received from the dealer, the Toyota 4Runner was equipped with a popular "value package" that included a wheel/tire upgrade from that installed on models not otherwise equipped. Wheel diameter was increased from 15 to 16 inches, and tire size from P225/75R-15 to P265/70R-16. No additional upgrade was available. Because this package also included larger front brakes, the smaller 15 inch wheels could not be installed due to caliper-to-rim interference.

[3] Wheel/tire outside diameter approximations are based on $RollingDiameter = 2 \times \frac{TireWidth \times AspectRatio}{25.4} + WheelDiameter$, and do not consider differences in sidewall deformation due to static loading.

Table 3.8. Phase IV OEM and Optional Wheel / Tire Summary.

Vehicle	As Delivered				Optional Package			
	Wheel	Tire			Wheel	Tire		
		Make	Model	Size		Make	Model	Size
2001 Escape	15" x 6.5"; Aluminum Alloy	General	Grabber AW	P225/70R-15 100S	16" x 7"; Aluminum Alloy	Firestone	Wilderness HT	P235/70R-16 104T
1999 ML320	16" x 8"; Aluminum Alloy	Dunlop	Grandtrek T.G. 35	255/65R-16 109H	17" x 8.5"; Aluminum Alloy	Dunlop	Grandtrek T.G. 35	275/55R-17 109H

3.4.3.2 Rear-Mounted Ballast

The Modified Handling configurations for the Toyota 4Runner and Chevrolet Blazer involved placement of ballast in the cargo area behind the rear seat. The ballast, which consisted of 25 lb bags of lead shot contained in a large, covered plywood container secured to the floor, was iteratively increased/positioned while the vehicle was on the VIMF at SEA. The ballast was great enough to achieve rear Gross Axle Weight Rating (GAWR) and vehicle Gross Vehicle Weight Rating (GVWR), yet positioned in a way that preserved the C.G height of the Nominal load configuration. The 4Runner required 818 lbs of ballast, which produced a 12.6 inch rearward shift of the vehicle's longitudinal C.G. location. The Blazer required 729 lbs of ballast (see Figure 3.4), which produced a 10.5 inch rearward shift of the vehicle's longitudinal C.G. location. Table 3.9 summarizes the rear-mounted ballast loading configuration.

Figure 3.4. Rear ballast positioned in the cargo area of the 2001 Chevrolet Blazer. A cover was placed over the box prior to testing.

Table 3.9. Rear-Mounted Ballast Configuration Summary.

Vehicle	GVWR (lbs)	Rear GAWR (lbs)	Required Rear Ballast (lbs)	Rearward Longitudinal C.G. Shift (inches)	C.G. Height Change From Nominal Load (inches)
2001 4Runner	5250	3000	818	12.6	-0.15 in
2001 Blazer	5000	2800	729	10.5	-0.06 in

In addition to changes in longitudinal C.G. position, the influence of rear-mounted ballast on 4Runner and Blazer mass moments of inertia was also measured at SEA. The results of these tests are provided in Table 3.10. Unlike the data presented in Tables 3.4 through 3.7, the data contained in Table 3.10 was recorded with fully instrumented vehicles. When compared to Nominal Load measurements, rear-mounted ballast increased pitch inertia by 35.5 percent for the 4Runner, and by 28.9 percent for the Blazer. Similar increases in yaw inertia were imposed by the addition of rear ballast; by 32.9 percent for the 4Runner, and by 27.5 percent for the Blazer. Increases in roll inertia were also observed, however due to the preservation of vertical C.G., the effect was much less than in pitch and yaw. Roll inertia increased by 2.6 percent for the 4Runner and by 4.9 percent for the Blazer.

Table 3.10. Influence of Rear-Mounted Ballast on Vehicle Mass Moments of Inertia.

Vehicle	Nominal Load (with instrumentation)			Rear Mounted Ballast Loading (with instrumentation)					
	Pitch Inertia (ft-lb-sec^2)	Roll Inertia (ft-lb-sec^2)	Yaw Inertia (ft-lb-sec^2)	Pitch Inertia (ft-lb-sec^2)	Increase from Nominal (%)	Roll Inertia (ft-lb-sec^2)	Increase from Nominal (%)	Yaw Inertia (ft-lb-sec^2)	Increase from Nominal (%)
2001 4Runner	2650.7	571.0	2863.7	3566.1	**35.5**	585.9	**2.6**	3806.1	**32.9**
2001 Blazer	2613.8	541.4	2827.3	3368.3	**28.9**	567.9	**4.9**	3604.0	**27.5**

Like the Reduced Rollover Resistance configuration, Modified Handling configurations were intended to be maneuver sensitivity checks. The manner in which the Modified Handling configuration achieved this objective, however, differed conceptually from that used for Reduced Rollover Resistance testing. Installation of optional wheel/tire packages were expected to "improve" the handling of their respective vehicles, while placement of rear-mounted ballast was expected to degrade it. These configurations were intended to allow the authors to assess whether the anticipated improvements or degradations of handling produced any adverse affects with respect to dynamic rollover propensity.

3.4.3.3 Comments on Modified Handling

For three of the four vehicles, the Modified Handling condition also served as a way of validating the SSF's ability to predict on-road, untripped rollover propensity. For these vehicles, the SSF remained essentially constant. Because SSF predicts no difference in rollover propensity between vehicles with the same value, this type of comparison was important.

In the case of the Mercedes ML320, the diameter of the optional wheel/tire package was approximately 0.14 inches less than that originally installed on the vehicle[4]. This package therefore had a negligible effect on the ML320's vertical C.G. and SSF. As previously shown in Table 3.9, the shift in C.G. height from the Nominal Load to Rear-Mounted Ballast condition for the Toyota 4Runner and Chevrolet Blazer was also negligible, thus preserving constant SSF values. The only vehicle for which a comparison of the Nominal Load to Modified Handling condition could not be performed due to differing SSF values was the Ford Escape. The Escape's optional wheel/tire package was approximately 1.6 inches greater than that originally installed on the vehicle[4]. This raised the vertical C.G. slightly, thus lowering the SSF.

Although neither Modified Handling configuration was intended to simulate real-world scenarios, the possibility of these configurations existing on actual roadways is very real. Optional wheel/tire packages approved by automakers are in evidence on the road, and rear-ballasted sport utility vehicles are frequently seen leaving home-improvement store parking lots.

3.4.4 Phase IV Static Stability Factor Summary

Table 3.11 presents the static stability factors (SSF) of each vehicle in the Baseline, Baseline with Outriggers, Nominal, Reduced Rollover Resistance, and Modified Handling configurations. Recall that measured/calculated SSFs of the Reduced Rollover Resistance condition do not include the effects of instrumentation. Based on the relationship of the Baseline with Outriggers and Nominal Load SSFs, the actual SSFs of the Reduced Rollover Resistance condition were likely 0.004 to 0.032 less than those reported in Table 3.11.

Table 3.11. Phase IV Static Stability Factors at Each Load Condition.

Vehicle	Baseline[1]	Baseline with Outriggers[1]	Nominal Load	Reduced Rollover Resistance[1]	Modified Handling
2001 Blazer	1.025	1.038	1.048	0.989	1.054
2001 4Runner	1.098	1.112	1.122	1.063[2]	1.123
1999 ML320	1.123	1.143	1.175	1.093[2]	1.177[3]
2001 Escape	1.232	1.263	1.267	1.211	1.226[3]

[1]Data do not include the effects of instrumentation.

[2]Estimated based with the method described in Section 3.4.2.

[3]Esimated based on the increased ride height predicted by comparing the outside diameter of the OEM wheel/tire package to that used in the Modified Handling Condition.

[4] Wheel/tire outside diameter approximations are based on $RollingDiameter = 2 \times \frac{TireWidth \times AspectRatio}{25.4} + WheelDiameter$, and do not consider differences in sidewall deformation due to static loading.

4.0 INSTRUMENTATION

Each Phase IV test vehicle was similarly instrumented with sensors, a data acquisition system, and a programmable steering machine. This chapter describes the test equipment, and how it was utilized. Separate subsections deal with two-wheel lift measurement and monitoring electronic stability control activations. A brief description of correction techniques applied to Reduced Rollover Resistance and Modified Handling acceleration data is also provided.

4.1 Sensors and Sensor Locations

Table 4.1 characterizes the sensors used to measure vehicle responses. Sensor types are listed with the data channel measured in the first column of the table. Additional columns list the sensor type, sensor range, sensor manufacturer, and sensor model number.

A multi-axis inertial sensing system was employed to measure three-axis linear accelerations and angular rates. The system package was placed very close to the center of gravity of each vehicle in its Nominal Load configuration so as to minimize roll, pitch, and yaw effects for the Nominal Load configuration testing. As discussed below, correction equations were used to account for change in location of the center of gravity for the Reduced Rollover Resistance and some Modified Handling vehicle configurations.

The multi-axis inertial sensing system does not provide inertial stabilization of its accelerometers. Lateral acceleration was corrected for vehicle roll angle effects during data post processing using the techniques that are explained in [4].

Handwheel position was recorded with an angle encoder integral with the programmable steering machine. For driver-based tests for which the steering machine was not installed, it was measured with a string-type rotary potentiometer attached to the steering column shaft.

An ultrasonic distance measurement system was used to collect left and right side vehicle ride heights for the purpose of calculating vehicle roll angle. One ultrasonic ranging module was mounted on each side of a vehicle. These sensors were positioned at each vehicle's longitudinal center of gravity.

Vehicle roll angle was computed from the output of the left and right ultrasonic height measurement sensors and the roll rate measured by the multi-axis inertial sensing system. Reference [4] presents the technique used.

Brake pedal force was measured with a load cell transducer attached to the face of the brake pedal.

Pressure transducers were installed in series with the hydraulic brake lines of vehicles equipped with stability control. One in-line transducer was installed at the junction of the hard and flexible brake lines at each road wheel brake assembly. The outputs of the pressure transducers were used to identify individual road wheel brake applications during stability control system intervention.

Table 4.1. Test Vehicle Sensor Information.

Data Measured	Type	Range	Manufacturer	Model Number
Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Multi-Axis Inertial Sensing System	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	BEI Technologies, Inc. Systron Donner Inertial Division	MotionPak Multi-Axis Inertial Sensing System MP-1
Handwheel Angle	Angle Encoder	Infinite	Automotive Testing, Inc.	Integral with ATI Steering Machine
Handwheel Angle (for maneuvers for which the Programmable Steering Machine was not used)	String Potentiometer	15 inches, Linear	UniMeasure	LX-PA-15
Left and Right Side Vehicle Ride Height	Ultrasonic Distance Measuring System	5-24 inches	Massa Products Corp.	Measurement System: M-4000-D Ranging Modules: M-410/150
Brake Pedal Force	Load Cell	0-300 lbf	GSE Inc.	4351
Brake Line Pressure	Pressure Transducer	0-2500 psia	PSI-Tronix, Inc.	PSI-100/2500-A2
Event Trigger Pulse	Diffuse Reflective Sensor	100-700 mm	SUNX Trading Co., Ltd.	RS-120H-1
Vehicle Speed	Radar Speed Sensor	0.1-125 mph	B+S Software und Messtechnik GmbH	DRS-6
Angular Displacement (Sine and Cosine) Longitudinal, Lateral, and Vertical Force Camber, Overturning, and Steer Moments	6-Component Wheel Load Transducer	Sine and Cosine: ±1 Force: ±6000 lbf Moment: ±6000 lbf-ft	Michigan Scientific Corporation	Wheel Load Transducer: LW12.8 Rotating Amplifier Modules: LWEH-6L Slip Ring/Resolver Assembly: SR20AW/R360/AX Resolver Electronic Unit: RESSC-2-12V

Data recording was triggered automatically during driver-controlled lane changes by employing a diffuse reflective sensor mounted to the exterior of each vehicle. The sensor reacted to a reflective panel placed on the road surface at the entrance of the course. Automatic data recording was used during these maneuvers to allow test drivers to concentrate on steering the test vehicles through the pylon-delineated courses.

Vehicle speed was measured with a non-contact Doppler radar sensor placed at the center rear of each vehicle. Sensor outputs were transmitted to the data acquisition system, to a display integral with the steering controller, and to a dashboard display unit.

4.2 Programmable Steering Machine

A programmable steering machine produced by Automotive Testing, Inc. (ATI) was used to provide steering inputs for all test maneuvers except the path-following lane changes. Descriptions of the steering machine, including features and technical specifications, have been previously documented and are available in [7, 15, and 16].

4.3 Six-Component Wheel Load Transducer

A six-component wheel load measurement system produced by Michigan Scientific Corporation was employed during selected tests to measure longitudinal, lateral and vertical forces, and camber, steer and torque moments at the left front road wheel of the Mercedes ML320 (see Figure 4.1). The system was composed of a wheel load transducer, a rotating amplifier module, and a slip ring/resolver assembly. Chassis-mounted modules contain resolver electronics and a power supply. An OEM alloy wheel rim was modified to accept the transducer, and a hub adapter connected the transducer to the axle hub.

Figure 4.1 Six-component wheel load transducer installed on the Mercedes ML320.

The elements of the assembled wheel package (a wheel rim, transducer, amplifier module, and slip ring/resolver) rotate about the wheel spindle axis. Electronic connections between the transducer, amplifier module, and slip ring/resolver assembly were made via fixed modular pin connectors.

Wheel forces and moments were derived from the outputs of strain gauge bridge circuits. The strain gauges were fixed to wheel spokes in the form of rigid beams that connect inner and outer rings of the wheel load transducer. The gauges respond to mechanical strains produced by physical inputs to the wheel.

The amplifier module was paired to a specific transducer. The slip ring/resolver assembly is mounted to the amplifier module. The angular position of the resolver rotor was fixed in relation to the accompanying transducer and its strain gauges. The resolver and related electronics provided analog sine and cosine outputs to identify the angular position of the assembled wheel package. Wheel angle sine and cosine data were used in post processing to resolve force and moment measurements between the wheel and chassis coordinate systems.

4.4 Data Acquisition

In-vehicle data acquisition systems recorded sensor outputs. Ruggedized industrial computers, each equipped with either a 500 MHz or a 600 MHz Pentium III microprocessor, collected data during the testing. The computers employed the DAS-64 data acquisition software developed by the NHTSA's Vehicle Research and Test Center. Analog Devices Inc. 3B series signal conditioners were employed to condition data signals from all transducers listed in Table 4.1. Measurement Computing Corporation PCI-DAS6402/16 boards digitized analog signals at a collective rate of 200 kHz. Final sample rates were set at 100 or 200 Hz depending on the type of maneuver. Test drivers initiated data collection prior to the start of maneuvers performed with the steering machine. As was discussed earlier, a reflective sensor was employed to trigger data collection during driver-based double lane changes.

Signal conditioning performed by the 3B signal conditioners consisted of amplification and filtering. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Filtering was performed using a two-pole low-pass Butterworth filter with the nominal cutoff frequencies selected to prevent aliasing. The calculated breakpoint frequencies were 18 and 19 Hz for the first and second poles, respectively. Higher nominal breakpoint frequencies of 1800 and 1900 Hz for the first and second poles, respectively, were used for the handwheel angle channel. These high filter frequencies were used to permit unwrapping of angle encoder data output from the steering controller. At 360 degrees, the encoder output jumps back to zero and proceeds from there. Unwrapping resolves this problem. However, if the data were filtered with 18 and 19 Hz breakpoint filters, the filtering prevented the unwrap function from working optimally (i.e., an artificial, filter induced, bump appeared in the data). Since the handwheel angle data were measured with an optical encoder with essentially no noise, despite the high filter breakpoint frequencies, aliasing was not a problem for this channel.

4.5 Characterization of Two-Wheel Lift

During past phases of NHTSA's Light Vehicle Rollover Research program, two-wheel lift has been categorized as Minor, Moderate, or Major. These categories were defined as follows:

- **Minor Two-Wheel Lift**. Both wheels departed from the roadway for only a short period of time (a fraction of a second) and the lower of the two wheels has a maximum lift of less than two inches off of the road. Frequently, Minor two-wheel lift cannot be detected by either the test driver or by test observers. Careful, frame-by-frame analysis of test video may well be necessary to determine whether Minor two-wheel lift occurred.

- **Moderate Two-Wheel Lift.** More than Minor but less than Major two-wheel lift. Test observers can generally detect moderate two-wheel lift present during a test.

- **Major Two-Wheel Lift.** The wheels lift so far off of the roadway that outriggers were required to suppress the vehicle's roll motion. If no outriggers were present, the vehicle might well have rolled over.

Experience has taught the authors that there are some problems in using these categories. Problems that have been identified include:

1. Minor two-wheel lift may provide a poor representation of a vehicle's dynamic rollover propensity. A vehicle that produces a lateral load transfer of almost, but not quite, 100 percent at a given test speed may not be any less likely to rollover than a vehicle that produces a fraction of an inch of two-wheel lift at the same speed. For some vehicles, minor two-wheel lift appears to occur due to suspension hop.

2. Sometimes there are substantial difficulties in determining whether or not minor two-wheel lift occurred. Standard VRTC practice is to videotape the tests. The test videos are later reviewed frame-by-frame to determine whether minor two-wheel lift occurred. However, for some tests the results of such a review are ambiguous. Different reviewers may disagree as to whether or not minor two-wheel lift occurred.

3. Major two-wheel lift is not objective. The roll angle at which major lift occurs depends to a large extent on the suspension characteristics of the vehicle. Some vehicles pitch or squat to a greater extent than others during rollover testing. This can substantially affect the roll angle at which the outriggers first touch the pavement.

4. The roll angle at which major two-wheel lift occurs also depends upon the height at which the outriggers are set. Dynamic rollover tests performed at VRTC begin with the outriggers set low for driver safety. In certain test conditions some vehicles required increased outrigger-to-pavement clearance because the initial setting did not allow for at least moderate two-wheel lift. While the raised height permitted observation of moderate lift, it also increased the maximum roll angle attainable at major lift. In this sense, "Major Lift" does not accurately and consistently describe maneuver severity, but simply that outrigger contact was made. For each vehicle, Table 4.2 presents the overall ranges of roll angles for which major two-wheel lift was produced during Phase IV testing.

Table 4.2. Overall Ranges of Roll Angles for which Major Two-Wheel Lift Was Observed During Phase IV Testing.

Vehicle	Roll Angle at Major TWL (degrees)
2001 Toyota 4Runner	13.7 – 19.6
2001 Chevrolet Blazer	10.5 – 15.8
2001 Ford Escape	15.1
1999 Mercedes ML320	9.4 – 11.2

If dynamic driving tests were to provide consumer information on rollover propensity, a more objective and more rollover-related categorization of two-wheel lift was needed. This was partially developed during the Phase IV research as follows:

1. The authors decided not to consider or report minor two-wheel lift. Its occurrence was no longer used as a termination condition for rollover resistance maneuvers.

2. The authors decided not to differentiate between moderate and major two-wheel lift. In this report the term two-wheel lift will be used to indicate that either moderate or major two-wheel lift occurred.

In many cases, moderate two-wheel lift occurred one speed iteration prior to major wheel lift. Although the iterative increase of speed was to cease once moderate lift had occurred, there were situations in which the experimenter was unable confirm the amount two-wheel lift produced during a particular test (by reviewing the test on the small screen of a handheld video recorder). If this was the case, speed was increased, and in many cases, major lift was produced.

Although they were not utilized for the tests performed in Phase IV, future dynamic rollover propensity tests performed at VRTC will use laser-based wheel height sensors to directly measure when at least two inches of simultaneous two-wheel lift occurs. At the time of this report, use of this technique was being evaluated. Preliminary findings are encouraging and demonstrate an excellent correlation with frame-by-frame video data reduction results.

4.6 Monitoring of Electronic Stability Control System Activation

Two Phase IV test vehicles were equipped with electronic stability control systems. These systems are designed to enhance safety by automatically supplementing driver inputs in extreme operating conditions. Electronic stability control systems attempt to limit understeer (plow out) or oversteer (spinout) via engine torque management and/or selective brake application at one or more wheels. The systems use various inputs and algorithms to determine when and in what manner intervention should occur.

Brake line transducers monitored brake applications in the electronic stability control' braking modes. Monitoring the other forms of intervention was facilitated by recording signals used to transmit visual or aural cues to the driver. The Mercedes Electronic Stability Program (ESP) illuminates an instrument panel indicator during any intervention. Similarly, the Toyota Vehicle Stability Control (VSC) system produces an audible warning and illuminates an instrument panel indicator during any intervention. In both vehicles, the data acquisition systems were configured to record the voltage changes in these driver interface circuits.

Throughout this report, many figures presenting Mercedes ML320 data feature "ESP Flag" plots. Similarly, "VSC Flag" data are often presented for the Toyota 4Runner. In either case, the presence of a signal indicates that stability control has determined a condition exists in which intervention had been deemed necessary. ESP and VSC Flag data show when this information is being conveyed to the driver.

4.7 Accelerometer Corrections for Changes in Center of Gravity Locations

As previously discussed in Chapters 2 and 3, ballast was added to the Phase IV vehicles for all Reduced Rollover Resistance tests. Additionally, ballast was used during Modified Handling tests performed with the Chevrolet Blazer and Toyota 4Runner. Although the centers of gravity changed for these vehicle configurations, the position of the multi-axis inertial sensing system (containing the three linear accelerometers) in each vehicle did not.

However, the extent to which the locations of the centers of gravity changed was known. This allowed measured acceleration data to be corrected for roll, pitch, and yaw effects, and translated to what actually occurred at the displaced centers of gravity.

The following equations were used to correct the accelerometer data in post-processing. They were derived from equations of general relative acceleration for a translating reference frame and use the SAE Convention for Vehicle Dynamics Coordinate Systems. The coordinate transformations are:

$$x''_{corrected} = x''_{accel} - (\Theta'^{\,2} + \Psi'^{\,2})x_{disp} + (\Theta'\Phi' - \Psi'')y_{disp} + (\Psi'\Phi' + \Theta'')z_{disp}$$

$$y''_{corrected} = y''_{accel} + (\Theta'\Phi' + \Psi'')x_{disp} - (\Phi'^{\,2} + \Psi'^{\,2})y_{disp} + (\Psi'\Theta' - \Phi'')z_{disp}$$

$$z''_{corrected} = z''_{accel} + (\Psi'\Phi' - \Theta'')x_{disp} + (\Psi'\Theta' + \Phi'')y_{disp} - (\Phi'^{\,2} + \Theta'^{\,2})z_{disp}$$

where

$x''_{corrected}$, $y''_{corrected}$, and $z''_{corrected}$ = longitudinal, lateral, and vertical accelerations, respectively, at the displaced enter of gravity

x''_{accel}, y''_{accel}, and z''_{accel} = longitudinal, lateral, and vertical accelerations, respectively, at the accelerometer location

x_{disp}, y_{disp}, and z_{disp} = longitudinal, lateral, and vertical displacements, respectively, of the center of gravity in reference to the accelerometer location

Φ' and Φ'' = roll rate and roll acceleration, respectively

Θ' and Θ'' = pitch rate and pitch acceleration, respectively

Ψ' and Ψ'' = yaw rate and yaw acceleration, respectively

5.0 SLOWLY INCREASING STEER

The Slowly Increasing Steer maneuver was one of five characterization maneuvers used in Phase IV. It was based on that used during Phase II of the Rollover Research program, however, the steering was input slightly faster and reached a greater maximum value. Like the other characterization maneuvers, the Slowly Increasing Steer maneuver used automated steering inputs generated by a programmable steering machine.

This chapter is comprised of six sections. Section 5.1 describes the maneuver and how it was executed. Section 5.2 and 5.3 discuss the steering and vehicle speed input repeatability, respectively. Section 5.4 discusses output repeatability. Section 5.5 presents test results. Section 5.6 provides a maneuver assessment and concluding remarks.

5.1 Maneuver Description

The Slowly Increasing Steer maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in SAE J266 [17].

Since seven of the twelve Phase II vehicles achieved their maximum lateral accelerations with handwheel inputs greater than 190 degrees, the authors believe that the 200 degree maximum steering input used during the Phase II research may have limited the maximum attainable lateral acceleration of the vehicles tested during that study. Therefore, the maximum handwheel angle was increased from 200 to 270 degrees for the Phase IV research. To maintain a steering rise time of 20.0 seconds, the handwheel steering rate was increased from 10.0 to 13.5 degrees per second.

To begin this maneuver, the vehicle was driven in a straight line at 50 mph. The driver was instructed to maintain as constant a test speed as possible before, during, and after the steering inputs using smooth throttle modulation. At time zero, handwheel position was linearly increased from zero to 270 degrees at a rate 13.5 degrees per second. Handwheel position was held constant at 270 degrees for two seconds, after which the maneuver was concluded. The handwheel was then returned to zero as a convenience to the driver. The maneuver was performed in two directions, to the left and to the right. Three repetitions of each test condition were performed. Figure 5.1 presents the actual handwheel angles recorded during a Slowly Increasing Steer test with the Chevrolet Blazer.

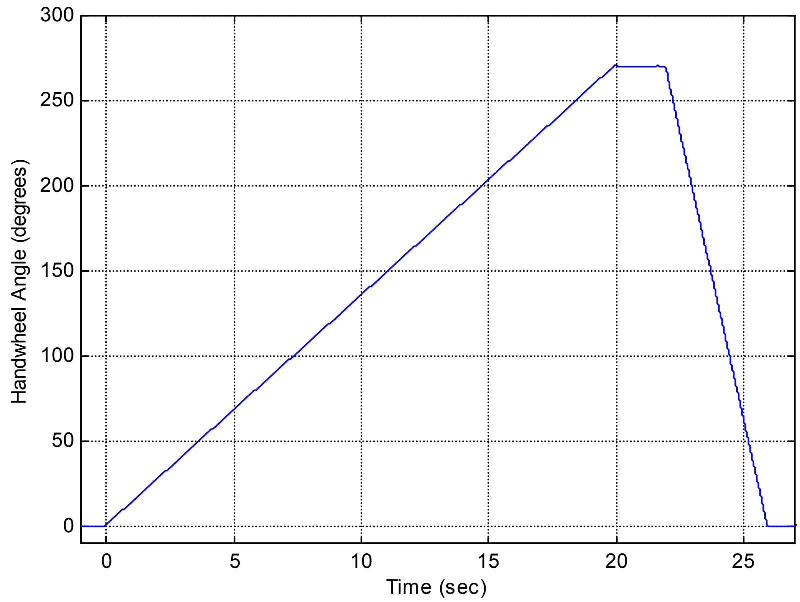

Figure 5.1. Handwheel inputs recorded during a Slowly Increasing Steer test with the Chevrolet Blazer.

5.2 Steering Input Repeatability

For each vehicle, three Slowly Increasing Steer repetitions were performed for both left and right steering. Because the commanded magnitude remained constant, a comparison of the handwheel inputs for each direction of steer was possible. Figure 5.2 Handwheel Angle data for six Mercedes ML320 runs (three with electronic stability control enabled and three with it disabled). The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the individual tests from each other.

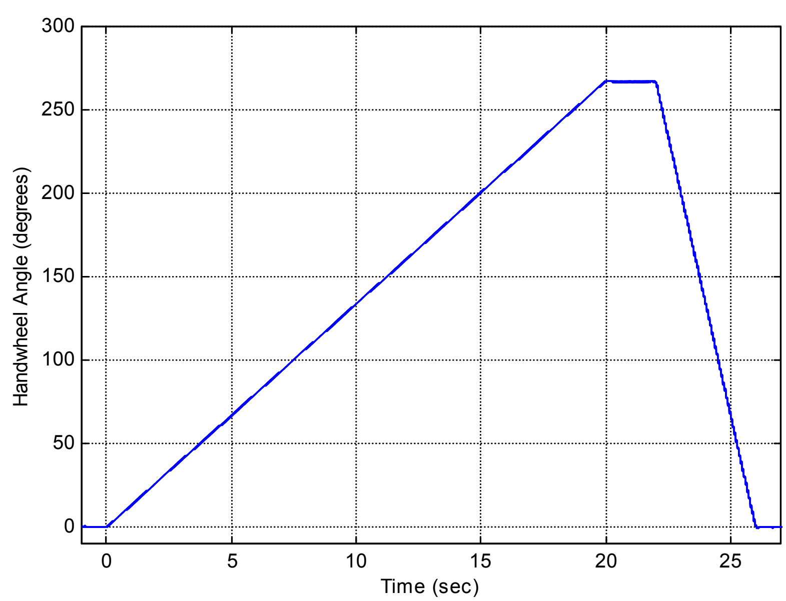

Figure 5.2. Handwheel inputs recorded during six Mercedes ML320 Slowly Increasing Steer tests. Tests were perfomed at 30 and 50 mph.

5.3 Vehicle Speed Input Repeatability

The Slowly Increasing Steer maneuver required the driver to maintain the vehicle speed as constant as possible via throttle modulation. Since electronic stability control intervention can have a significant effect on vehicle speed during this maneuver, this section contains comparisons of vehicle speed recorded during tests performed with enabled and disabled stability control. Note, therefore, that these comparisons were based on results produced from two unique test series[1].

Figure 5.3 presents handwheel position, vehicle speed, and stability control intervention data for six Slowly Increasing Steer tests performed with the Mercedes ML320. Three tests were performed with stability control, three were not. The nominal speed of these tests was 50 mph, and speed was to be held as constant as possible for the duration of the maneuver. When stability control was active, intervention was observed approximately 8.5 seconds after time zero. During this particular test, stability control electronically removed the driver's throttle inputs but no brake application occurred. Nevertheless, this slowed the vehicle significantly, lowering speed from approximately 50 mph to approximately 22 mph. As Figure 5.3 shows, the manner in which speed reduction occurred was very consistent.

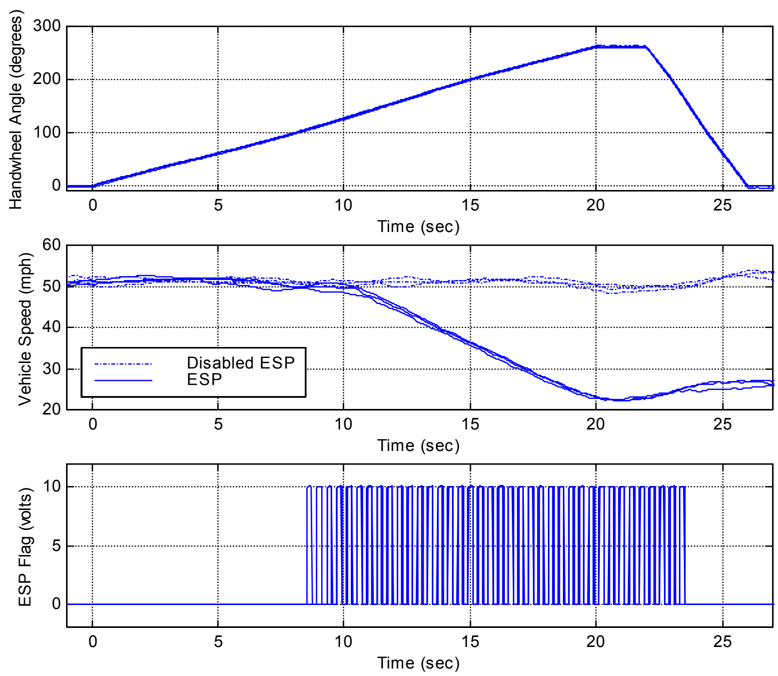

Figure 5.3. Handwheel inputs recorded during six Mercedes ML320 Slowly Increasing Steer tests with enabled and disabled electronic stability control.

[1] In Phase IV, a vehicle with enabled electronic stability control was considered to be different than the same vehicle with disabled stability control. As such, tests performed with enabled and disabled stability control used different tire sets. This was to minimize any confounding effects of tire wear may have had on vehicle response (i.e., due to the sequence in which the maneuvers were performed; enabled first, then disabled, or visa versa).

5.4 Output Repeatability

For each vehicle, three Slowly Increasing Steer test repetitions were performed for each direction of steering. Because the commanded handwheel magnitude and vehicle speed remained constant, test output comparisons of the three similar tests run with the same direction of steer were possible. Figure 5.4 presents these data for three tests, in the Nominal Load configuration, with the Mercedes ML320. Stability control was disabled for these tests. The excellent test output repeatability makes it nearly impossible to distinguish the individual tests from each other.

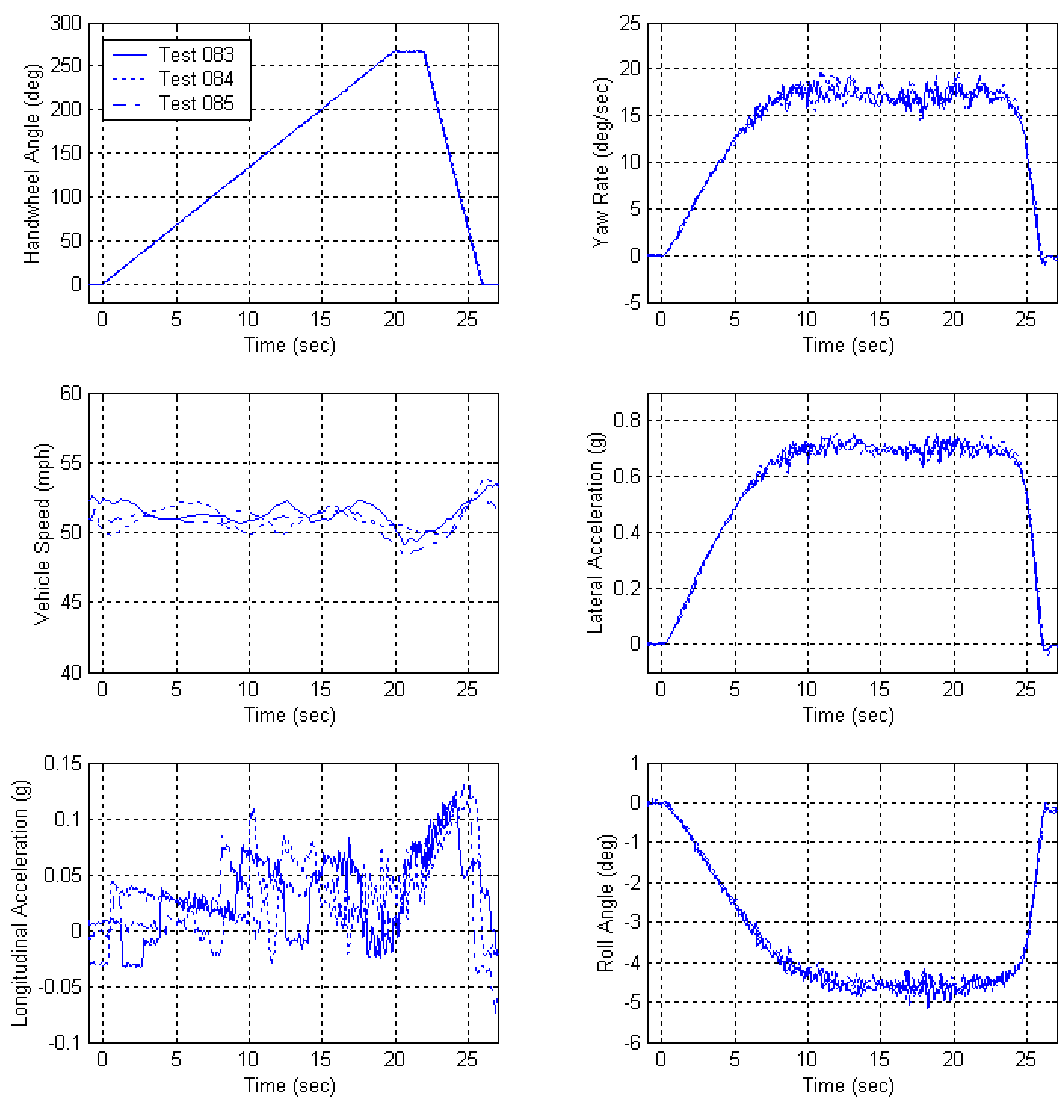

Figure 5.4. Test outputs recorded during three Mercedes ML320 Slowly Increasing Steer tests.

5.5 Results

5.5.1 Maximum Lateral Acceleration

Use of the Slowly Increasing Steer maneuver was one of two ways the maximum quasi-steady state lateral acceleration of each test vehicle was determined.

5.5.1.1 Determination of Maximum Lateral Acceleration

As maximum lateral acceleration was approached, during the Slowly Increasing Steer maneuver (also the Slowly Increasing Speed maneuver), the noise level in the lateral accelerometer signal became substantial. When data were filtered at 6 Hz during post processing (using a 12-pole, phaseless, Butterworth, digital filter), this noise influenced which maxima were extracted during data analysis from some tests. The brief duration of the "spikes" associated with accelerometer noise, especially in the quasi-steady state established after tires had reached saturation, made their occurrence more anomalous than meaningful.

To reduce the effect of noise in the lateral acceleration signal on maximum lateral acceleration, the raw data was processed using 0.3, 0.4, and 0.5 second running-average filters. Each filter duration reduced peak values from those observed for data simply filtered at 6 Hz. In the authors' opinion, for a majority of the lateral acceleration data, the 0.4 second running average filter was the most appropriate, providing the best compromise between fit to the 6Hz filtered data and noise reduction. Therefore, this has been selected as the second stage filter for determining maximum lateral acceleration.

Figure 5.5 presents a comparison of Slowly Increasing Steer data filtered with just the 6 Hz, 12-pole, phaseless, Butterworth digital filter and with the 0.4 second running-average filter. This data is from a test performed with the Mercedes ML320 in the Nominal Load configuration. When only filtered at 6 Hz, the maximum lateral acceleration for this test was 0.80 g. Substituting the 0.4 second running average filter reduced the maximum lateral acceleration value to 0.77 g, and shifted the time of its occurrence back 5.1 seconds. In the opinion of the authors, when the peak lateral acceleration occurred does not matter based on the uses that we make of this data.

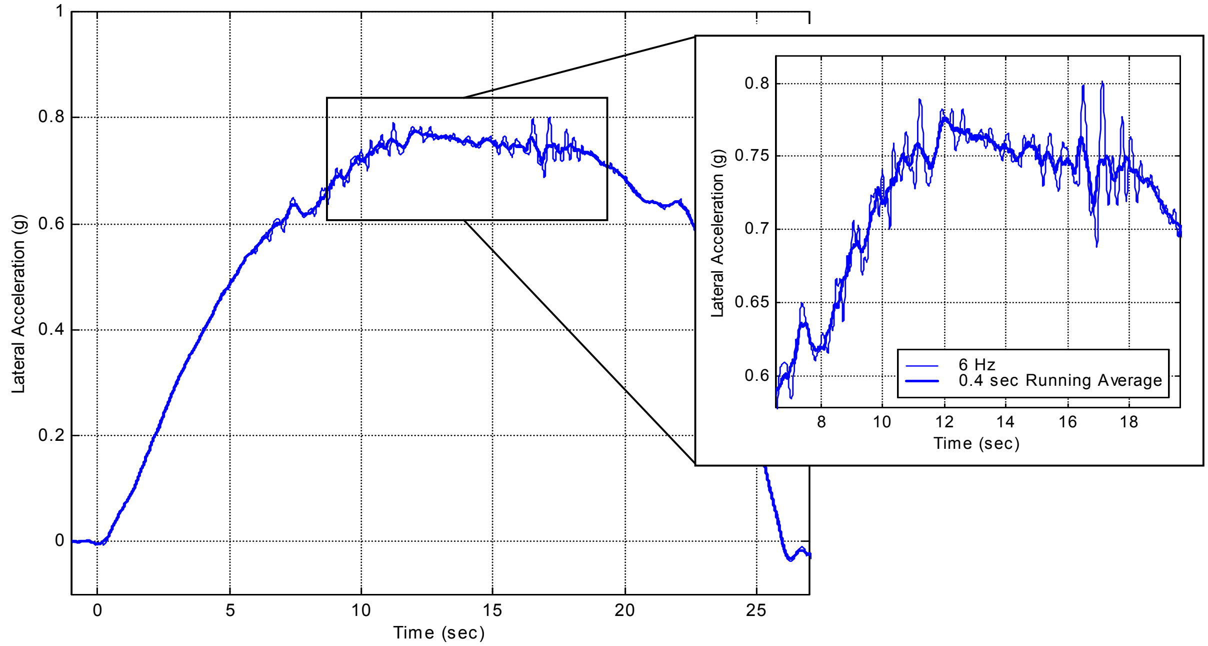

Figure 5.5. Lateral acceleration measured during a Slowly Increasing Steer Maneuver performed with the Mercedes ML320 in the Nominal Load configuration. 6 Hz, 12-pole, phaseless Butterworth or 0.4 second running average filters were applied to the data during post-processing.

Table 5.1 presents maximum lateral accelerations recorded for the Phase IV vehicles in each vehicle configuration. Data filtered 6 Hz, as well as that processed with a 0.4 second running-average, are provided[2]. Averages for left steering, right steering, and overall are given. Only the maximum lateral accelerations determined from data filtered with both the 0.4 second running-average filter will be discussed in the remainder of this section.

All data presented in Table 5.1 have been corrected for the C.G. displacement imposed by the Reduced Rollover Resistance and certain Modified Handling test configurations where appropriate.

[2] Table 5.1 presents data filtered at 6 Hz simply to demonstrate that trends in the data remain constant regardless of which filtering technique was applied (e.g., differences in peak values when left as opposed to right steering was input). The 0.4 second running average filter reduced the overall peak lateral accelerations of data filtered at 6 Hz by up to 6.1 percent. The average reduction was 2.3 percent.

Table 5.1. Average Maximum Lateral Accelerations Using 6 Hz, 12-Pole, Phaseless, Butterworth and 0.4 Second Running Average Filters.

Vehicle	Configuration	Left Steer (g)		Right Steer (g)		Overall (g)	
		6 Hz	0.4 Second Running Average	6 Hz	0.4 Second Running Average	6 Hz	0.4 Second Running Average
2001 Toyota 4Runner w/VSC	Nominal	0.78	0.77	0.73	0.72	**0.76**	**0.74**
	Reduced Rollover Resistance	0.75	0.75	0.70	0.68	**0.73**	**0.71**
	Modified Handling	0.75	0.75	0.77	0.76	**0.76**	**0.75**
2001 Toyota 4Runner w/o VSC	Nominal	0.76	0.73	0.73	0.72	**0.74**	**0.72**
	Reduced Rollover Resistance	0.75	0.74	0.73	0.71	**0.74**	**0.73**
	Modified Handling	0.73	0.72	0.76	0.74	**0.75**	**0.73**
2001 Chevrolet Blazer	Nominal	0.74	0.73	0.76	0.74	**0.75**	**0.74**
	Reduced Rollover Resistance	0.77	0.71	0.75	0.71	**0.76**	**0.71**
	Modified Handling	0.73	0.72	0.73	0.72	**0.73**	**0.72**
2001 Ford Escape	Nominal	0.79	0.78	0.80	0.78	**0.79**	**0.78**
	Reduced Rollover Resistance	0.77	0.76	0.75	0.74	**0.76**	**0.75**
	Modified Handling	0.78	0.77	0.77	0.75	**0.78**	**0.76**
1999 Mercedes ML320 w/ESP	Nominal	0.80	0.79	0.79	0.77	**0.79**	**0.78**
	Reduced Rollover Resistance	0.82	0.80	0.79	0.77	**0.81**	**0.79**
	Modified Handling	0.79	0.76	0.81	0.80	**0.80**	**0.78**
1999 Mercedes ML320 w/o ESP	Nominal	0.79	0.77	0.75	0.74	**0.77**	**0.75**
	Reduced Rollover Resistance	0.77	0.75	0.77	0.74	**0.77**	**0.75**
	Modified Handling	0.77	0.76	0.80	0.78	**0.78**	**0.77**

5.5.1.2 Nominal Load Maximum Lateral Accelerations

The maximum lateral acceleration produced with the Chevrolet Blazer using right steer inputs (0.74 g) was 1.4 percent greater than that produced with left steering (0.73 g). Overall, the maximum lateral acceleration achieved by the Blazer was 0.74 g.

The maximum lateral acceleration produced with the Ford Escape using right steer inputs was identical to that produced with left steering (0.78 g).

The maximum lateral acceleration produced with the Toyota 4Runner occurred when left steering was applied, regardless of whether electronic stability control was enabled or disabled. When stability control was enabled, average left steer maximum lateral acceleration (0.77 g) was 5.9 percent greater than the average right steer value (0.72 g). In both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, the average left steer maximum lateral acceleration (0.73 g) was only slightly greater than the average right steer value (0.72 g), differing by 1.4 percent. The overall maximum lateral accelerations of the 4Runner, with enabled and disabled stability control, were 0.74 g and 0.72 g, respectively.

As with the Toyota 4Runner, the maximum lateral acceleration produced with the Mercedes ML320 occurred when left steering was applied, regardless of whether electronic stability control was enabled or disabled. When stability control was enabled, average left steer maximum lateral acceleration (0.79 g) was 2.6 percent greater than the average right steer value (0.77 g). In both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, average left steer maximum lateral acceleration (0.77 g) was 4.1 percent greater than the average right steer value (0.74 g). The overall maximum lateral accelerations of the ML320, with enabled and disabled stability control, were 0.78 g and 0.75 g, respectively.

5.5.1.3 Reduced Rollover Resistance Maximum Lateral Accelerations

The maximum lateral acceleration produced by the Chevrolet Blazer in the Reduced Rollover Resistance configuration with right steering (0.71 g) was equivalent to that produced with left steering. The overall maximum lateral acceleration achieved by the Blazer in this configuration was 4.1 percent less than that produced in the Nominal Load configuration (0.74 g).

The maximum lateral acceleration produced by the Ford Escape in the Reduced Rollover Resistance configuration with left steering (0.76 g) was 2.7 percent greater than the right steer value (0.74 g). Overall, the maximum lateral acceleration achieved by the Escape was 0.75 g, 3.8 percent less than that produced in the Nominal Load configuration (0.78 g).

Like the Ford Escape, the maximum lateral acceleration produced by the Toyota 4Runner in the Reduced Rollover Resistance configuration occurred when left steering was applied, regardless of whether electronic stability control was enabled or disabled. When stability control was enabled, the average left steer maximum lateral acceleration (0.75 g) was 10.3 percent greater than the average right steer value (0.68 g). In both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, average left steer maximum lateral acceleration (0.74 g) was in better agreement with the average right steer value (0.71 g), differing by 4.2 percent. The overall maximum lateral accelerations for the 4Runner, with enabled and disabled stability control, were 0.71 g and 0.73 g, respectively. With enabled stability control, the overall average value was 4.1 percent less than that of the Nominal Load configuration (0.74 g). When stability control was disabled, however, the overall maximum lateral acceleration was slightly greater (1.4 percent) with Reduced Rollover Resistance loading than for the Nominal Load configuration (0.72 g).

In agreement with Ford Escape and Toyota 4Runner results in this configuration, the Mercedes ML320 in the Reduced Rollover Resistance configuration produced maximum lateral acceleration when left steering was applied, regardless of whether electronic stability control was enabled or disabled. When stability control was enabled, the average left steer maximum lateral acceleration (0.80 g) was 3.9 percent greater than the average right steer value (0.77 g). In both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, average left steer maximum lateral acceleration (0.75 g) was only 1.4 percent greater than the average right steer value (0.74 g). The overall maximum lateral accelerations of the ML320, with enabled and disabled stability control, were 0.79 g and 0.75 g, respectively. The overall maximum lateral acceleration produced in the Reduced Rollover configuration, with enabled stability control, was slightly greater (1.3 percent) than that of the Nominal Load configuration (0.78 g). When stability control was disabled, however, the overall values produced in each configuration were identical. Also in agreement with the Nominal Load configuration results, the ML320 produced maximum overall lateral acceleration with stability control enabled.

5.5.1.4 Modified Handling Maximum Lateral Accelerations

In agreement with the Reduced Rollover Resistance configuration results, the maximum lateral acceleration produced by the Chevrolet Blazer in the Modified Handling configuration with right steering (0.72 g) was equivalent to that produced with left steering. The overall maximum lateral acceleration achieved by the Blazer with modified handling was 2.7 percent less than that produced in the Nominal Load configuration (0.74 g), and slightly greater (1.4 percent) than that produced in the Reduced Rollover Resistance configuration (0.71 g).

The maximum lateral acceleration produced by the Ford Escape in the Modified Handling configuration with left steering (0.77 g) was 2.7 percent greater than the right steer value (0.75 g). The maximum lateral acceleration achieved by the Escape (0.76 g), was 2.6 percent less than that produced in the Nominal Load configuration (0.78 g), and slightly greater (1.3 percent) than that produced in the Reduced Rollover Resistance configuration (0.75 g).

Although the Toyota 4Runner required left steering to yield maximum lateral acceleration in the Nominal Load and Reduced Rollover Resistance configurations, input of *right* steering produced maximum lateral acceleration in the Modified Handling configuration, regardless of whether electronic stability control was enabled or disabled. When enabled, the average maximum lateral acceleration for tests performed with steering to the right (0.76 g) was 1.3 percent greater than the average left steer value (0.75 g). In both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, the average maximum lateral acceleration for tests performed with steering to the right (0.74 g) was 2.8 percent greater than the average left steer value (0.72 g). The overall maximum lateral accelerations of the 4Runner in the Modified Handling configuration, with enabled and disabled stability control, were 0.75 g and 0.73 g, respectively.

The overall peak values obtained by the 4Runner in the Modified Handling configuration were 1.4 percent greater than those produced in the Nominal Load configuration, regardless of electronic whether stability control was enabled or disabled. The overall maximum lateral acceleration produced in the Modified Handling configuration with stability control was 5.6 percent greater than that produced with Reduced Rollover Resistance tests. However, when stability control was disabled, the values were equivalent.

Like the Toyota 4Runner, the Mercedes ML320 required left steering to yield maximum lateral acceleration in the Nominal Load and Reduced Rollover Resistance configurations, regardless of whether electronic stability control was enabled or disabled. However, the ML320 required input of *right* steering to produce maximum lateral acceleration in the Modified Handling configuration. When enabled, the average maximum lateral acceleration for tests performed with steering to the right (0.80 g) was 5.3 percent greater than the average left steer value (0.76 g). For both directions of steer, stability control intervention was in evidence before, during, and after maximum lateral acceleration occurred. When stability control was disabled, the average maximum lateral acceleration for tests performed with steering to the right (0.78 g) was 2.6 percent greater than the average left steer value (0.76 g). The overall maximum lateral accelerations of the ML320 in the Modified Handling configuration, with enabled and disabled stability control, were 0.78 g and 0.77 g, respectively.

The overall maximum lateral acceleration of the ML320 obtained with stability control, in the Modified Handling configuration, was equivalent to that produced in the Nominal Load configuration (0.78 g). It was 1.3 percent less than the Reduced Rollover Resistance configuration value. When stability control was disabled, the overall maximum lateral acceleration produced with modified handling was 2.7 percent greater than that produced in the Nominal Load or Reduced Rollover Resistance configurations (0.75 g).

5.5.2 Understeer Gradient

In addition to determining maximum lateral acceleration, data collected during the Slowly Increasing Steer maneuver was used to calculate the understeer gradients of each vehicle using SAE J266, Equation 16 [17]. Table 5.2 presents the understeer gradients for each vehicle configuration.

Handwheel steering angle and vehicle speed collected at lateral accelerations ranging from 0.1 to 0.4 g were used to calculate understeer gradients. Due to the low lateral accelerations while collecting this data, stability control intervention was not observed for tests performed with the Toyota 4Runner and Mercedes ML320. For this reason, stability control status information (whether it was active or disabled for a particular test series) is simply a way of distinguishing two test series in this section; the data produced by each series should be equivalent.

5.5.2.1 Nominal Load Understeer Gradients

With the exception of the Ford Escape and Mercedes ML320 with disabled stability control, the average understeer gradients observed in the Nominal Load configuration were greater (had more understeer) when the Slowly Increasing Steer maneuver was performed with steering to the right. The degree to which these values differed was vehicle dependent.

The range of understeer gradients calculated for the Escape in the Nominal Load configuration using left steer data was entirely within the range established by right steer data. An opposite trend was observed for the ML320 when tested with enabled stability control; the range of understeer gradients calculated using right steer data was entirely within the range established by left steer data. When the ML320 was evaluated without stability control, the average understeer gradients of tests performed in each direction of steer differed; there was some overlap in the data. One of three left steer tests was within the range of values calculated with right steer data.

In contrast to the results produced with the Escape and ML320 in the Nominal Load configuration, the ranges of understeer gradients calculated for the Toyota 4Runner and Chevrolet Blazer using left steer were entirely outside the range established using right steer data. For these vehicles, every test performed with left steering produced understeer gradients less than those calculated with right steer data.

In the Nominal Load configuration, the overall average understeer gradients of the Ford Escape and Chevrolet Blazer were 4.21 and 5.98 deg/g, respectively. The overall composite (calculated with data collected during tests performed both with stability enabled *and* disabled) understeer gradients for the Toyota 4Runner and Mercedes ML320 were 3.68 and 2.95 deg/g, respectively.

Table 5.2. Understeer Gradients Calculated From Slowly Increasing Steer Tests.

Vehicle	Configuration	Left Steer (deg/g)			Right Steer (deg/g)			Overall (deg/g)	
		Range	Average	Std Dev	Range	Average	Std Dev	Average	Std Dev
2001 Toyota 4Runner w/VSC	Nominal	3.14 – 3.32	3.22	0.09	3.93 – 4.20	4.05	0.14	**3.64**	**0.47**
	Reduced Rollover Resistance	3.80 – 4.17	4.00	0.19	4.31 – 4.55	4.45	0.12	**4.23**	**0.28**
	Modified Handling	2.33 – 2.56	2.48	0.13	2.90 – 3.15	3.06	0.14	**2.77**	**0.34**
2001 Toyota 4Runner w/o VSC	Nominal	3.26 – 3.58	3.45	0.17	3.78 – 4.20	4.01	0.21	**3.73**	**0.35**
	Reduced Rollover Resistance	3.81 – 4.14	4.00	0.17	4.59 – 4.78	4.68	0.10	**4.34**	**0.39**
	Modified Handling	2.24 – 2.62	2.41	0.20	2.77 – 2.92	2.83	0.08	**2.62**	**0.27**
2001 Chevrolet Blazer	Nominal	5.14 – 5.64	5.45	0.27	6.39 – 6.56	6.50	0.09	**5.98**	**0.60**
	Reduced Rollover Resistance	4.94 – 5.94	5.30	0.56	6.61 – 7.02	6.85	0.21	**6.07**	**0.93**
	Modified Handling	3.98 – 4.24	4.13	0.13	4.79 – 5.20	5.03	0.21	**4.58**	**0.52**
2001 Ford Escape	Nominal	4.17 – 4.31	4.23	0.07	4.04 – 4.38	4.18	0.18	**4.21**	**0.13**
	Reduced Rollover Resistance	4.45 – 4.72	4.55	0.15	5.09 – 5.50	5.28	0.20	**4.92**	**0.43**
	Modified Handling	2.96 – 3.18	3.07	0.11	3.41 – 3.55	3.47	0.07	**3.27**	**0.24**
1999 Mercedes ML320 w/ESP	Nominal	2.87 – 3.33	3.05	0.25	2.96 – 3.14	3.03	0.09	**3.04**	**0.17**
	Reduced Rollover Resistance	3.21 – 3.85	3.78	0.29	3.86 – 4.04	3.95	0.09	**3.78**	**0.29**
	Modified Handling	3.59 – 3.93	3.71	0.19	3.93 – 4.44	4.11	0.29	**3.91**	**0.31**
1999 Mercedes ML320 w/o ESP	Nominal	2.49 – 2.89	2.69	0.20	2.81 – 3.30	3.02	0.25	**2.85**	**0.27**
	Reduced Rollover Resistance	3.00 – 3.16	3.10	0.09	3.60 – 3.99	3.78	0.20	**3.44**	**0.39**
	Modified Handling	3.19 – 3.50	3.39	0.18	3.79 – 4.06	3.90	0.14	**3.65**	**0.31**

5.5.2.2 Reduced Rollover Resistance Configuration Understeer Gradients

When left steer maneuvers were considered for the Toyota 4Runner with disabled stability control in the Reduced Rollover Resistance configuration, the entire range of understeer gradients calculated were within the range established by tests performed with enabled stability control. However, when right steering was considered, enabled stability control tests were entirely outside the range established with disabled stability control data. Because no stability control intervention was observed during the time for which understeer gradient data were considered, these differences were attributable to the test-to-test variability.

The entire range of disabled stability control tests performed in the Reduced Rollover Resistance configuration with left steering was outside that established with enabled stability control for the Mercedes ML320. However, when right steer maneuvers were considered, there was significant overlap of the two ranges. Because no stability control intervention was observed during the time for which understeer gradient data were considered, these differences were attributable to the test-to-test variability.

All average understeer gradients calculated with data collected during Reduced Rollover Resistance tests (for each vehicle) were greater when the Slowly Increasing Steer maneuvers were performed with steering to the right. The overall average understeer gradients of the Ford Escape and Chevrolet Blazer were 4.92 and 6.07 deg/g, respectively. The overall composite (calculated with data collected during tests performed both with stability enabled *and* disabled) understeer gradients for the Toyota 4Runner and Mercedes ML320 were 4.28 and 3.61 deg/g, respectively.

When compared with results produced during tests performed in the Nominal Load configuration, each vehicle produced more understeer in the Reduced Rollover Resistance configuration. The overall average understeer gradient increases for the Chevrolet Blazer, Ford Escape, Mercedes ML320, and the Toyota 4Runner were 1.5, 16.9, 16.3, and 22.3 percent, respectively.

5.5.2.3 Modified Handling Configuration Understeer Gradients

When left steer results in the Modified Handling configuration were considered, the entire range of understeer gradients calculated for Toyota 4Runner with enabled stability control were within the range established with disabled stability control. However, when right steer maneuvers were considered, there was significant overlap of the two ranges. Because no stability control intervention was observed during the time for which understeer gradient data were considered, these differences were attributable to the test-to-test variability.

The entire range of disabled stability control tests performed in the Modified Handling configuration with left steering was outside that established with enabled stability control for the Mercedes ML320. However, when right steer maneuvers were considered, there was significant overlap of the two ranges. Because no stability control intervention was observed during the time for which understeer gradient data were considered, these differences were attributable to the test-to-test variability.

With the exception of the Mercedes ML320 with disabled stability control, all average understeer gradients calculated with data collected during Modified Handling tests (for each vehicle) were greater when the Slowly Increasing Steer maneuvers were performed with steering to the right. When evaluated with enabled stability control, the ranges of understeer gradients calculated for the Mercedes ML320 using left steer were almost entirely outside the range established using right steer data (the greatest left steer understeer gradient was equivalent to the smallest right steer value).

The overall average understeer gradients of the Ford Escape and Chevrolet Blazer in the Modified Handling configuration were 3.27 and 4.58 deg/g, respectively. The overall composite understeer gradients for the Toyota 4Runner and Mercedes ML320 were 2.69 and 3.78 deg/g, respectively.

With the exception of the Mercedes ML320, the overall average understeer gradients calculated for each vehicle in the Modified Handling configuration were less those produced with Nominal Load configuration data. The overall average understeer gradient decreases for the Chevrolet Blazer, Ford Escape, and the Toyota 4Runner were 23.4, 22.3, and 26.9 percent, respectively. When compared with Nominal Load configuration data, the overall average understeer gradient of the ML320 increased by 28.1 percent in the Modified Handling configuration.

5.6 Slowly Increasing Steer Discussion and Conclusion

5.6.1 Summary of Results

Slowly Increasing Steer tests provided a simple and objective way of measuring maximum lateral acceleration with good repeatability, while simultaneously generating data required for understeer gradient calculation. Unlike the Slowly Increasing Speed maneuver, only one series of Slowly Increasing Steer tests were required to produce maximum lateral acceleration and understeer gradient results.

Handwheel input repeatability was excellent. Vehicle speed input repeatability was very good, but was strongly influenced by stability control intervention.

The use of a 0.4 second running average filter reduced the occurrence of anomalous peaks when compared with data filtered with a 6 Hz, 12-pole, phaseless, Butterworth, digital filter during post-processing. This technique reduced the overall maximum lateral acceleration by an average of 2.3 percent. Depending on the vehicle and test condition, average reductions of up to 6.1 percent were observed.

The Slowly Increasing Steer maneuver was able to quantify how the Reduced Rollover Resistance and Modified Handling configurations affected the vehicles lateral acceleration responses. Changes in linear range responses and maximum attainable lateral acceleration were apparent.

In the Nominal Load and Modified Handling configurations, the overall maximum lateral accelerations produced with the Toyota 4Runner and Mercedes ML320 were greatest with enabled electronic stability control. Test performed with disabled stability control produced overall maximum values 1.3 to 3.8 percent less than comparable tests performed with enabled stability control.

In the Reduced Rollover Resistance configuration, the overall maximum lateral acceleration of the ML320 with enabled electronic stability control was 5.1 percent greater than that produced when stability control was disabled. Conversely, the overall maximum lateral acceleration of the Toyota 4Runner with enabled stability control was 2.8 percent less than that produced when stability control was disabled.

5.6.2 A Maneuver Feasibility Issue

The primary disadvantage of the Slowly Increasing Steer maneuver is that it requires considerable testing real estate. The driver required an 800 by 800 ft square section of the TRC's VDA to comfortably perform the maneuver (two-thirds of the VDA's width and just over one-half on its useable length).

Although the concept was not investigated in Phase IV, increasing the handwheel rate of steer from that used in Phase IV (13.5 degrees/second) could potentially reduce the facility dimensions required by the maneuver. Unfortunately, this would necessarily reduce the amount of time the vehicle operated in the linear range of lateral acceleration. If the amount of time within the linear range becomes too small, the confidence with which this range is accurately determined may be compromised. For reasons that will become more evident later in this report, this would be highly undesirable. A more practical solution may be to segment the maneuver. One segment could be used to generate lateral accelerations in the linear range, since only a small amount of steering is required to define this region. A second segment could then be used to generate the maximum lateral value.

6.0 Development of Phase IV NHTSA J-Turn and Fishhook Maneuvers

The NHTSA J-Turn and Fishhooks 1a and 1b were dynamic rollover propensity maneuvers used in Phase IV of the Rollover Research program. Both feature improvements from corresponding maneuvers used during Phase II. This chapter discusses how these improvements were developed, and an explanation of why the chosen methodology is superior to alternatives.

This chapter is comprised of four sections. Section 6.1 presents background information. Section 6.2 explores the concept of relating J-Turn and Fishhook handwheel magnitudes to the handwheel magnitude at maximum lateral acceleration in the Slowly Increasing Steer maneuver. Section 6.3 presents alternatives to the method introduced in Section 6.2 by relating J-Turn and Fishhook handwheel magnitudes to other lateral accelerations observed in the Slowly Increasing Steer maneuver. These magnitudes include those at 75 percent of maximum lateral acceleration, at 0.6 g, and at 0.3 g. Section 6.4 introduces the method ultimately selected to define NHTSA J-Turn and Fishhook handwheel inputs.

6.1 Background

Relating J-Turn and Fishhook steering inputs to those producing known lateral accelerations was first suggested to NHTSA by Ford Motor Company following the release of the NHTSA Technical Report "An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover - Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program" [6]. During correspondence with VRTC, Ford expressed concerns that the Phase II J-Turn and Fishhook maneuvers failed to address differences in the handwheel inputs required to saturate a vehicle's tires. Ford suggested that steering at some percentage of the handwheel angle required to achieve maximum lateral acceleration, multiplied by a scalar to insure tire saturation, would guarantee maneuver severity while not giving vehicles with low steering gain an undeserved advantage.

In early 2000, NHTSA explored this approach through the use of characterization maneuvers during Phase III-A of its Light Vehicle Rollover Research Program. Although Phase III-A testing was based on only one vehicle (a 1998 Chevrolet Tracker), the study validated the concept, and demonstrated such maneuvers were capable of producing two-wheel lift.

In spring 2001, the Agency began the Phase IV rollover research. In an attempt to implement the best form of the methodology proposed by Ford, data produced with Phase IV vehicles, combined with that previously recorded during Phase II, was considered in detail. Specifically, the handwheel angles corresponding to maximum lateral acceleration, 75 percent of maximum lateral acceleration, 0.6 g, and 0.3 g were considered for use in defining the J-Turn and Fishhook steering inputs.

6.2 Use of Handwheel Position at Maximum Lateral Acceleration

Using the Slowly Increasing Steer procedure described in Chapter 5, the maximum lateral acceleration of each vehicle was measured. Tests were performed at 50 mph, with clockwise and counter-clockwise steering. Each direction of steering was repeated three times to monitor repeatability. In this investigation, the 4Runner and ML320 were evaluated without stability control. Table 6.1 presents the handwheel magnitudes when the maximum lateral acceleration was recorded for each of the Phase IV vehicles. The ranges (from the six tests), averages, and standard deviations of these data are provided.

Note that it is probable that the maximum *attainable* lateral acceleration of each vehicle was not achieved for the Slowly Increasing Steer tests performed during the Phase II research. Seven of the twelve Phase II vehicles achieved their maximum lateral accelerations for handwheel inputs greater than 190 degrees. The maximum commanded handwheel angle for these tests was 200 degrees. Although the idea of potentially relating J-Turn and Fishhook steering inputs to handwheel data observed at maximum lateral acceleration was of interest, the authors believed exploring such a concept could be potentially confounded by the questionable Phase II data. For this reason, Phase II data was not considered for any method that endeavored to relate fishhook and J-Turn steering to handwheel data observed at maximum lateral acceleration. The Phase IV Slowly Increasing Steer tests used a maximum handwheel angle of 270 degrees so as to ensure that vehicles reached their maximum attainable lateral acceleration.

Table 6.1. Handwheel Angles at Maximum Lateral Acceleration.

Vehicle	Handwheel Angle (degrees)									Lateral Acceleration (g)								
	Left Steer			Right Steer			Overall			Left Steer			Right Steer			Overall		
	Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev/ Ave (%)	Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev/ Ave (%)
Chevrolet Blazer	248 - 271	258	11.7	266 – 270	268	2.3	**263**	**9.2**	**3.5**	0.73 – 0.76	0.74	0.02	0.76 – 0.77	0.76	0.01	**0.75**	**0.01**	**1.3**
Toyota 4Runner (no VSC)	138 - 169	157	16.4	152 – 173	164	10.7	**161**	**13.0**	**8.1**	0.75 – 0.77	0.76	0.01	0.72 – 0.74	0.73	0.01	**0.74**	**0.02**	**2.7**
Mercedes ML320 (no ESP)	154 - 218	196	36.0	160 – 267	201	57.5	**199**	**43.0**	**21.6**	0.75 – 0.78	0.77	0.02	0.76 – 0.77	0.77	0.00	**0.77**	**0.01**	**1.3**
Ford Escape	238 - 261	252	12.5	213 – 243	232	16.4	**242**	**17.3**	**7.2**	0.78 – 0.80	0.79	0.01	0.77 – 0.81	0.80	0.02	**0.79**	**0.01**	**1.3**

Although the overall maximum lateral acceleration variability of each vehicle was quite low (the greatest standard deviation was 0.02 g), the steering used to achieve these values was quite disparate, especially for some vehicles. This disparity degrades the confidence by which the handwheel angle best associated with maximum lateral acceleration can be chosen; a problem if these inputs are to form the basis by which to derive Fishhook and J-Turn steering magnitudes.

Figure 6.1 illustrates this discrepancy by presenting two tests performed with the Mercedes ML320. Vehicle speed, handwheel angle, and lateral acceleration data are presented. Stability control was disabled. For these two tests, vehicle speed, steering inputs, and maximum lateral acceleration are nearly equal. Test 1 (solid line) required 218 degrees of steer to achieve maximum lateral acceleration. Test 2 (dashed line) required 154 degrees, 29 percent less than Test 1.

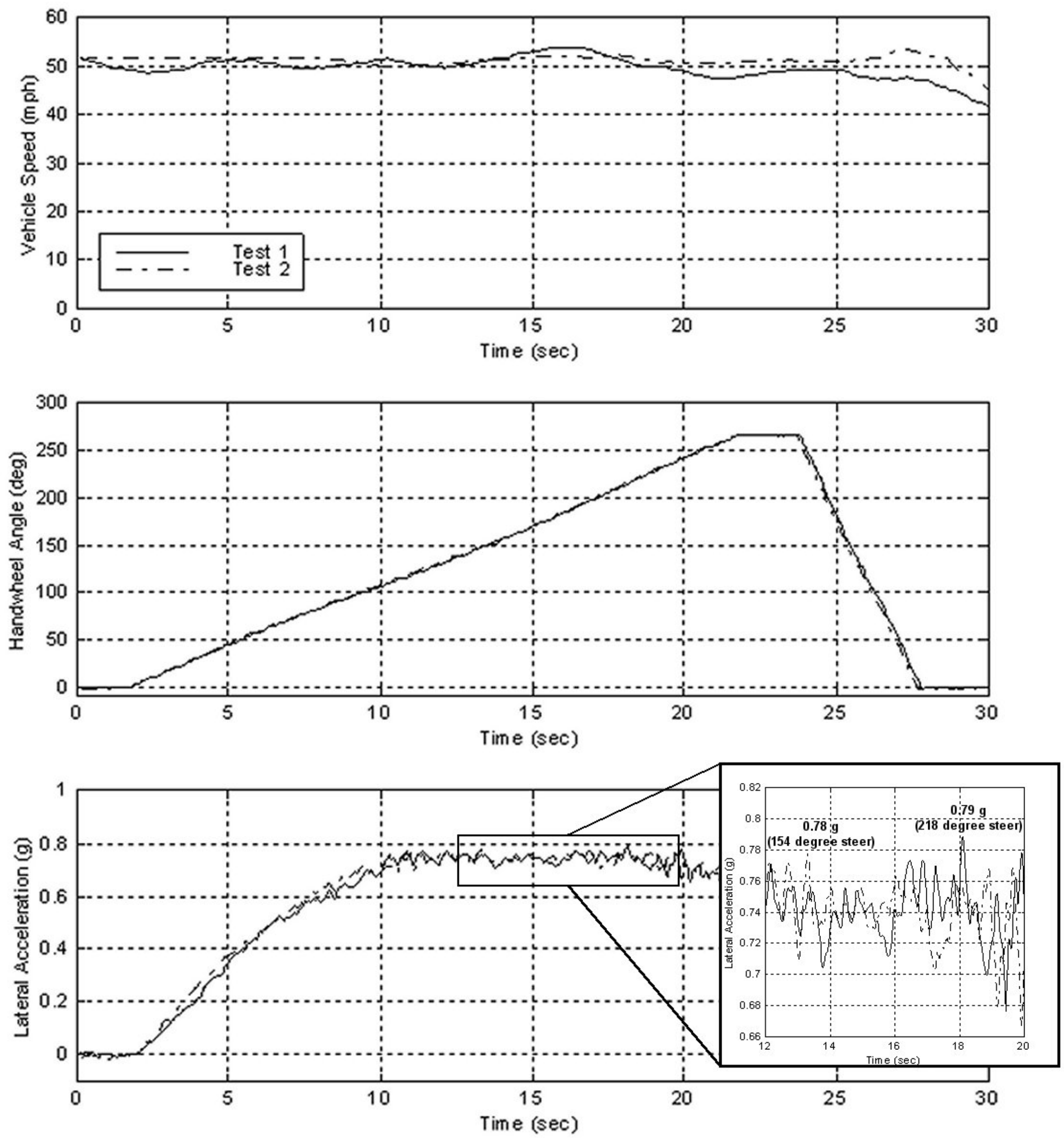

Figure 6.1. Handwheel input variability at maximum lateral acceleration.

In some cases, lateral acceleration traces produced by Slowly Increasing Steer tests included two significant peaks. The first peak typically occurred at or near saturation of the tires. Secondary peaks typically occurred later in the maneuver, and were often associated with substantially larger handwheel magnitudes.

The presence of multiple lateral acceleration peaks of nearly equal magnitude complicates the determination what the most "appropriate" handwheel angle should be: that associated with the first (primary) or second peak. Figure 6.2 illustrates this dilemma. Handwheel position, vehicle speed, and lateral acceleration data are provided for a test performed with the Mercedes ML320. First consider the data filtered with a 6 Hz digital Butterworth filter during post-processing of the data. The primary lateral acceleration peak was 0.789 g, and required 143 degrees of steer. The secondary peak was 0.793 g, and required 212 degrees. The two lateral acceleration peaks differ by only 0.5 percent.

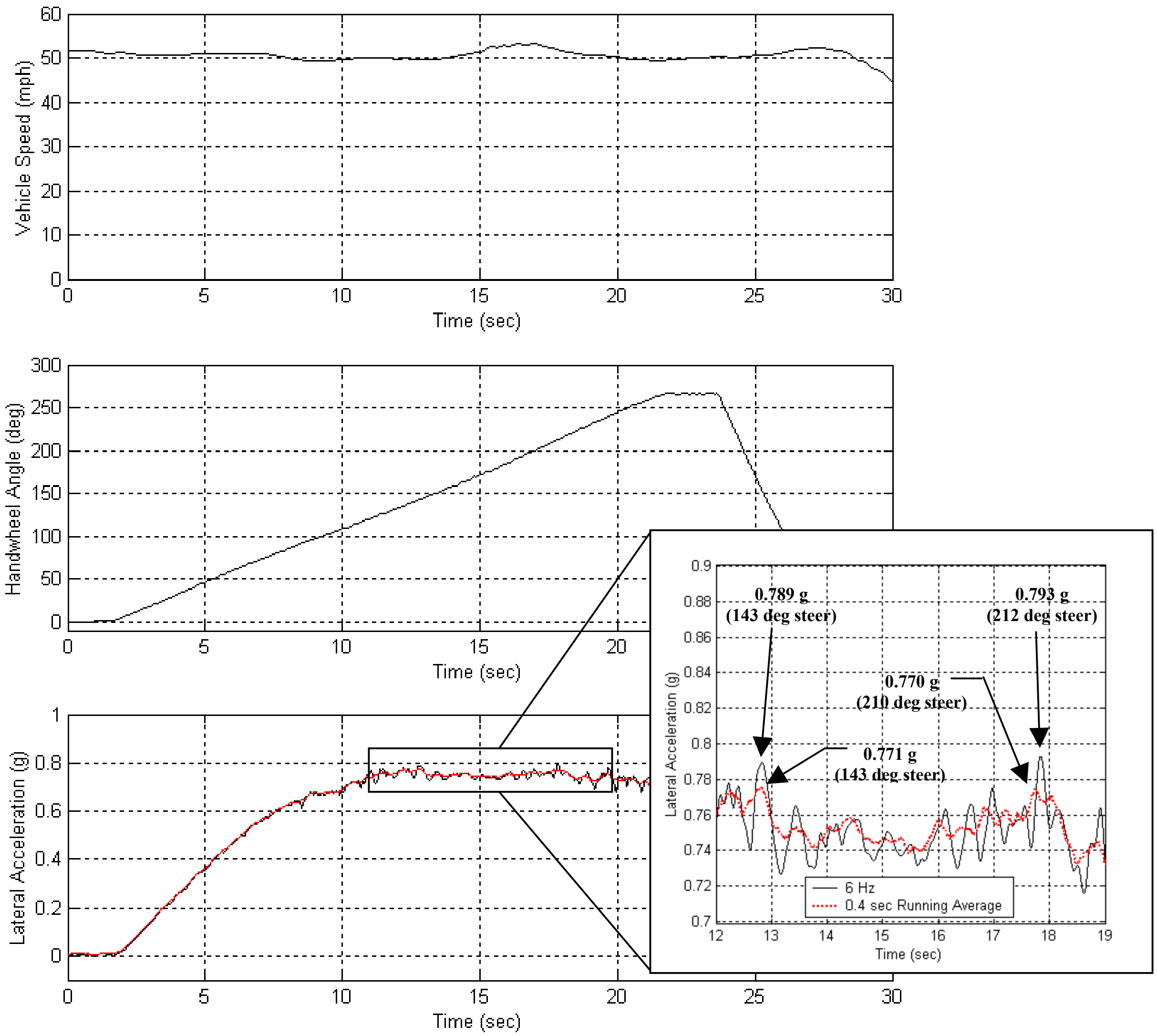

Figure 6.2. Comparison of handwheel input variability at primary and secondary lateral acceleration peaks.

In this example, the authors believe most appropriate lateral acceleration peak would be the first. This is important because it demonstrates that if a test procedure was to simply require use of the handwheel position at maximum *overall* lateral acceleration (for J-Turn and Fishhook steering determination), subsequent inputs could be potentially exaggerated.

In an attempt to address this concern, the raw format of the 6 Hz data presented in Figure 6.2 was processed with a 400 ms running-average filter (identical to that previously described in Section 6.5.1.1). Although the magnitudes of the primary and secondary peak lateral accelerations remained were nearly identical (they differed by only 0.1 percent), use of this more aggressive filter shifted the occurrence of maximum lateral acceleration back from the secondary peak to the primary peak for this particular test. Given the similarity of the peaks, however, it is unlikely that this technique can ensure that maximum lateral acceleration will always occur at the first peak.

Interestingly, stability control intervention had very little effect on the handwheel magnitude used to achieve maximum lateral acceleration. Although the related drive torque reduction and/or selective brake application reduced maneuver speed considerably, the overall handwheel position with enabled and disabled stability control differed by only 0.5 percent with the Mercedes ML320 (198 vs. 199 degrees), and by 2.1 percent with the Toyota 4Runner (157 vs. 161 degrees). Figures 6.3 and 6.4 further illustrate this point by comparing two representative Slowly Increasing Steer tests for each vehicle.

Figure 6.3 presents ML320 data recorded with enabled and disabled stability control. This figure features an "ESP Flag" data channel in the second row of the first column. This channel monitored illumination of the ESP indicator lamp in the instrument cluster of the ML320, and indicates the time over which stability control intervention occurred. This was required because while intervention often involved brake application (detectable via brake line pressure), it could also involve reduction of engine output (not detectable without receiving a signal directly from the ESP electronic control unit).

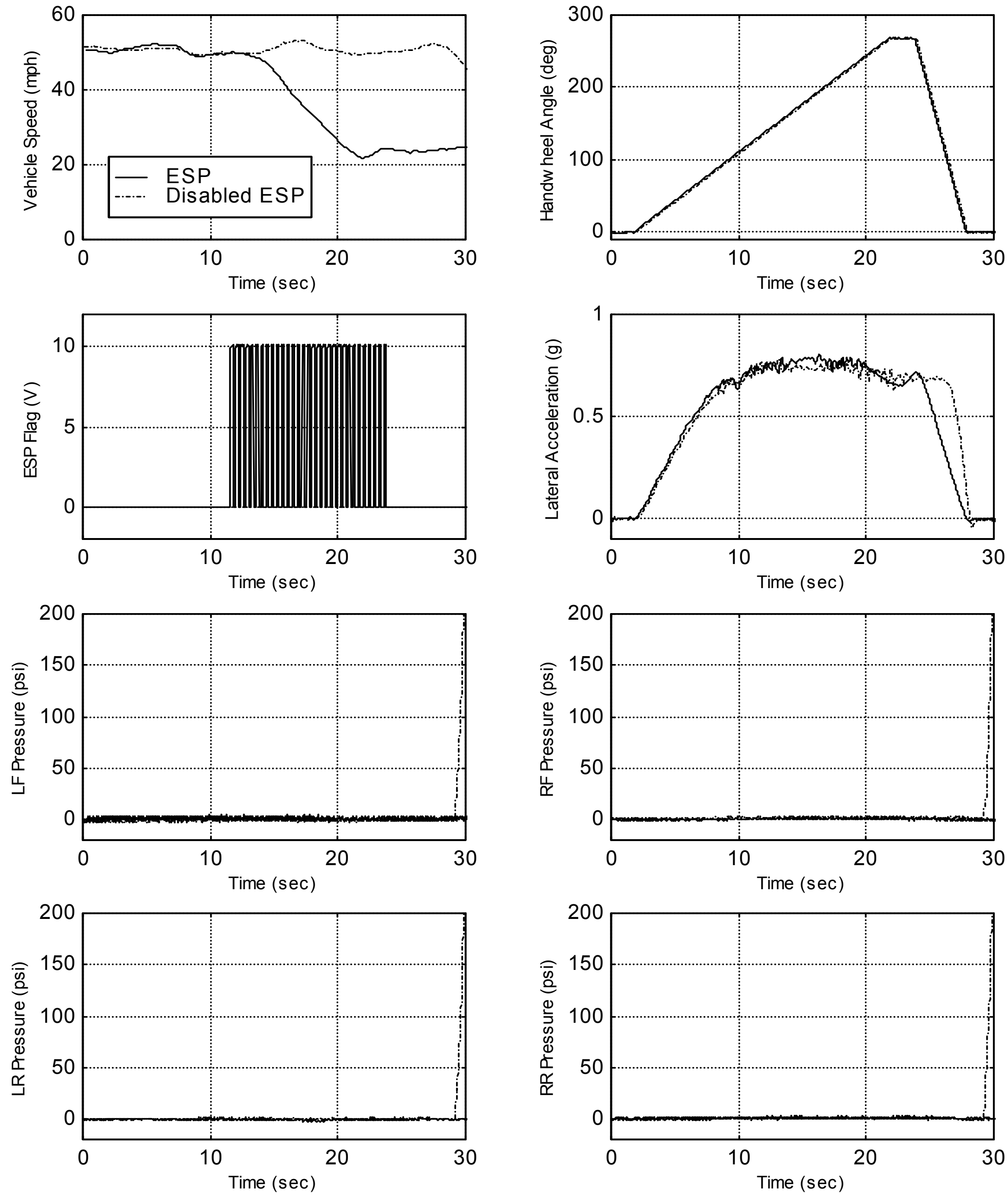

Figure 6.3. Inputs and outputs recorded during two Slowly Increasing Steer tests performed with enabled and disabled stability control with the Mercedes ML320.

Figure 6.4 shows 4Runner data recorded with enabled and disabled stability control. In a manner similar to that described for Figure 6.3, Figure 6.4 features a "VSC Flag" data channel. This channel is equivalent to the ESP Flag channel for the ML320 data.

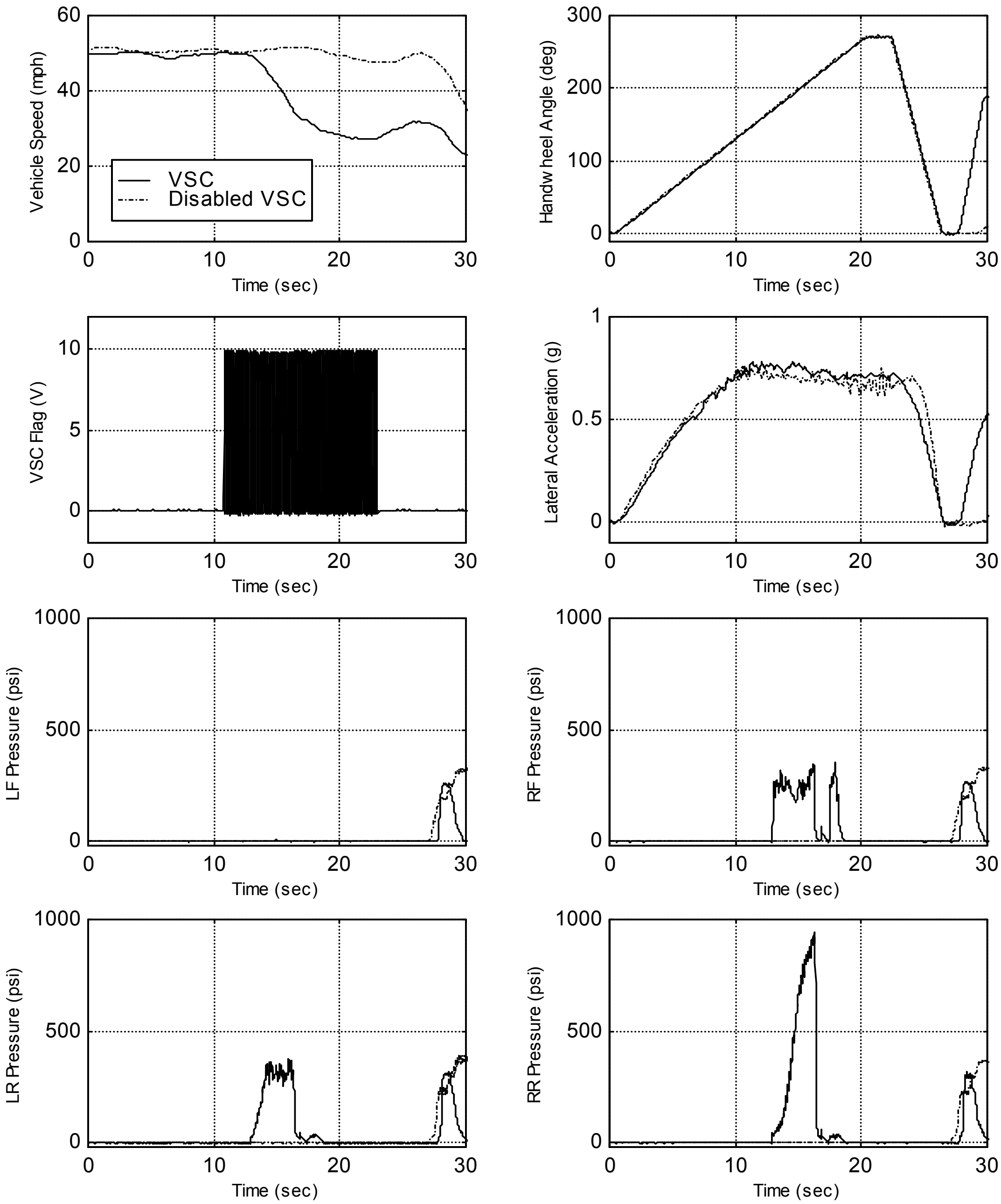

Figure 6.4. Inputs and outputs recorded during two Slowly Increasing Steer tests performed with enabled and disabled stability control with the Toyota 4Runner.

The concept of relating J-Turn and Fishhook handwheel inputs (for a particular vehicle) to those observed at maximum lateral acceleration had strong appeal. However, the handwheel angle variability measured at maximum lateral acceleration was too great to consider the method for further development.

6.3 Improving Steering Input Methodology

6.3.1 Objectives

Handwheel variability at maximum lateral acceleration is a problem for any procedure relying on these inputs to define the handwheel profiles for subsequent maneuvers. Furthermore, any error resulting from selection of an inappropriate magnitude is exaggerated when handwheel data is multiplied by a scalar intended to insure tire saturation. Although such variability impaired the feasibility of relating handwheel inputs to maximum lateral acceleration, the authors believed that the use of some other lateral acceleration based criteria had merit. To address previous shortcomings, three objectives were established to define future methodology:

1. The variability of the handwheel inputs used to define J-Turn and Fishhook steering must be low.

2. The method used to determine handwheel inputs must not be confounded by stability control intervention.

3. The scalars used to insure tire saturation must be applicable and appropriate to all light vehicles.

6.3.2 Use of Handwheel Position at 75 Percent of Maximum Lateral Acceleration

In an attempt to eliminate some disadvantages of defining J-Turn and Fishhook steering profiles with the handwheel inputs observed at maximum lateral acceleration, use of the handwheel position at 75 percent of the maximum lateral acceleration was considered. Using data collected during the Slowly Increasing Steer maneuver, the handwheel variability associated with this approach was investigated.

Table 6.2 presents the handwheel data observed at 75 percent of the maximum lateral acceleration recorded for the Phase IV vehicles. Depending upon the vehicle, the lateral accelerations corresponding to these inputs ranged from 0.56 to 0.60 g. Lateral acceleration data were found to be much cleaner in this region of the curve than near maximum lateral acceleration. When taken as a percentage of the mean, the overall handwheel variability of the data at 75 percent of the maximum lateral acceleration was lower than that presented in Table 6.1 (data collected at maximum lateral acceleration) for all vehicles but the Chevrolet Blazer. Note that stability control intervention was not observed at or before 75 percent of maximum lateral acceleration during 4Runner and ML320 testing, eliminating any possibility that its activation is confounding the data.

Table 6.2. Handwheel Angles at 75 Percent of Maximum Lateral Acceleration.

Vehicle	Handwheel Angle (degrees)									Lateral Acceleration (g)								
	Left Steer			Right Steer			Overall			Left Steer			Right Steer			Overall		
	Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev /Ave (%)	Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev /Ave (%)
Chevrolet Blazer	101 – 114	107	6.5	116 – 128	123	6.5	**115**	**10.5**	**9.1**	0.55 – 0.57	0.56	0.01	0.57 – 0.58	0.57	0.00	**0.56**	**0.01**	**1.8**
Toyota 4Runner (no VSC)	85 - 100	92	7.0	87 – 91	89	1.9	**91**	**5.0**	**5.5**	0.56 – 0.58	0.57	0.01	0.54 – 0.55	0.55	0.01	**0.56**	**0.01**	**1.8**
Mercedes ML320 (no ESP)	77 - 85	80	4.1	78 – 84	81	2.9	**81**	**3.2**	**4.0**	0.58 – 0.59	0.59	0.00	0.56	0.56	0.00	**0.57**	**0.02**	**3.5**
Ford Escape	100 – 101	100	0.6	97 – 103	101	3.1	**101**	**2.0**	**2.0**	0.59 – 0.60	0.59	0.01	0.58 – 0.61	0.60	0.02	**0.60**	**0.01**	**1.7**

Handwheel variability measured at 75 percent of maximum lateral acceleration, as measured by the average of the standard deviations as a percentage of the average angle in Table 6.1 and 6.2 was one-half that measured for maximum lateral acceleration (5.2 percent versus 10.4 percent).

While this was a positive finding, the authors thought that the methodology developed would be sounder if it were based on data from more than just the four Phase IV test vehicles. The logical additional data to use (since it was available) was that collected during the Phase II research.

As was discussed above, the Phase II lateral acceleration data probably did not attain the actual maximum lateral acceleration for several of the Phase II test vehicles due to the 200 degree maximum steering angle used during Phase II Slowly Increasing Steer testing. Therefore, to permit use of the Phase II data, two lateral acceleration levels, 0.6 and 0.3 g were considered.

6.3.3 Phase II Test Data

The Phase II test vehicle fleet was comprised of a broad range of vehicles chosen to be representative of many light vehicles. A combination of twelve vehicles, equally divided between automobiles, pickup trucks, sport utility vehicles, and vans, were selected. Table 6.3 lists the Phase II vehicles.

Table 6.3. NHTSA Phase II Test Vehicles.

Model Year	Make	Model	Classification
1998	Chevrolet	Lumina	Automobile
1998	Chevrolet	Metro	Automobile
1998	Dodge	Neon	Automobile
1998	Chevrolet	C1500 (2WD)	Pickup
1998	Chevrolet	S-10 (2WD)	Pickup
1997	Ford	Ranger (4WD)	Pickup
1998	Chevrolet	Tahoe (4WD)	Sport Utility Vehicle
1998	Chevrolet	Tracker (4WD)	Sport Utility Vehicle
1998	Ford	Explorer (4WD)	Sport Utility Vehicle
1998	Chevrolet	Astro (2WD)	Minivan
1998	Dodge	Caravan (2WD)	Minivan
1998	Ford	E150 Club Wagon (2WD)	Van

6.3.4 Use of Handwheel Position at 0.6 g

The use of handwheel inputs obtained from a lateral acceleration of 0.6 g in the Slowly Increasing Steer maneuver will now be explored. This research was performed concurrently with that exploring the use of handwheel angles at 75 percent of maximum lateral acceleration; it was happenstance that 75 percent of maximum lateral acceleration was very near the 0.6 g level discussed in this section. Unlike the previous section, however, research using handwheel angles at 0.6 g included data collected with both Phase II and Phase IV test vehicles.

The lateral acceleration versus handwheel angle data traces about 0.6 g were much cleaner than near the region containing maximum lateral acceleration. Figure 6.5 presents the lateral acceleration response of a constant speed, slowly increasing steer test performed during Phase II testing with the Chevrolet Metro. Note the noise in the data above approximately 0.6 g.

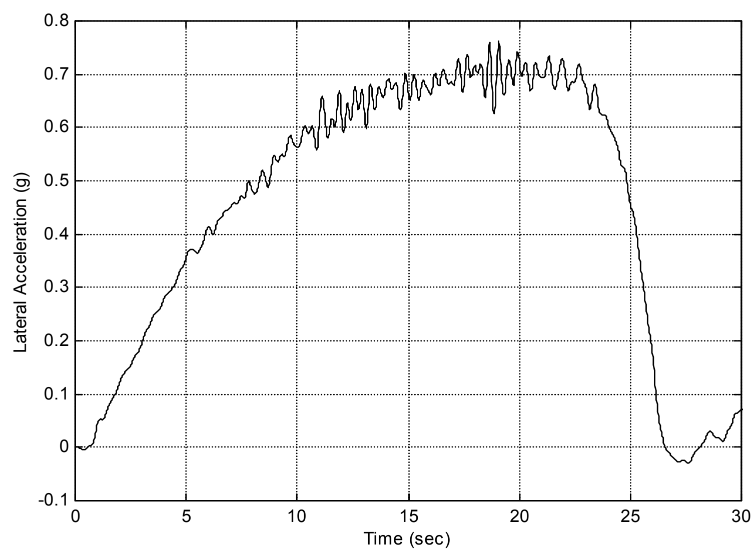

Figure 6.5. Lateral acceleration data produced during a Slowly Increasing Steer test performed with the Chevrolet Metro in Phase II.

Table 6.4 presents the handwheel magnitude data observed when lateral acceleration was at 0.6 g for all Phase II and IV vehicles. For each vehicle, ranges, averages, and standard deviations are provided.

First, consider only the Phase IV test vehicles. In agreement with the previous section, handwheel angles at 0.6 g were more repeatable than those based directly on maximum lateral acceleration. As a percentage of the mean, the average handwheel variability for the 0.6 g lateral acceleration data for these four vehicles was 4.2 percent versus 5.2 percent for those collected at 75 percent of maximum lateral acceleration and 10.4 percent for those collected at maximum lateral acceleration

Table 6.4. Handwheel Angles at 0.6 g Lateral Acceleration.

Fleet	Vehicle	Left Steer (degrees)			Right Steer (degrees)			Overall (degrees)		
		Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev (%)
Phase II	Lumina	77 – 86	83	5.1	93 – 104	99	5.5	**91**	**9.9**	**10.9**
	Metro	82 – 84	83	0.6	94 – 97	96	1.8	**90**	**7.4**	**8.3**
	Neon	71 – 72	71	0.9	78 – 84	82	3.5	**76**	**6.3**	**8.3**
	C1500	87 – 93	90	2.6	94 – 98	96	2.5	**93**	**3.7**	**4.0**
	S-10	80 – 91	86	5.2	83 – 90	87	4.7	**86**	**4.4**	**5.1**
	Ranger	83 – 104	94	10.5	107 – 115	110	3.7	**103**	**10.6**	**10.3**
	Tahoe	90 – 98	94	4.0	97 – 109	104	5.9	**99**	**6.9**	**7.0**
	Tracker	90 – 91	91	0.7	84 – 104	91	11.4	**91**	**7.2**	**7.9**
	Explorer	77 – 94	84	8.9	81 – 95	88	6.8	**86**	**7.3**	**8.5**
	Astro	144 – 166	155	11.2	125 – 137	129	6.9	**142**	**16.5**	**11.6**
	Caravan	96 – 107	101	5.3	102 – 111	107	4.5	**104**	**5.5**	**5.3**
	E150	80 – 82	81	1.3	88 – 98	94	5.4	**88**	**8.1**	**9.2**
Phase IV	Blazer	122 – 133	127	5.3	137 – 143	141	3.5	**134**	**8.5**	**6.3**
	4Runner	98 – 102	100	2.3	99 – 103	101	2.3	**101**	**2.2**	**2.2**
	ML320	80 – 85	82	3.0	88 – 91	89	1.5	**86**	**4.5**	**5.3**
	Escape	100 – 104	102	2.4	101 – 108	104	3.8	**103**	**3.0**	**2.9**

Now consider both the Phase II and Phase IV data. As a percentage of the mean, the average handwheel variability for the 0.6 g lateral acceleration data for all 16 vehicles was 7.1 percent versus 4.2 percent for just the Phase IV vehicles. This increase in variability occurred for two reasons. First, we believe that VRTC's experimental technique has improved (especially in the measurement of large roll angles; this effects lateral acceleration since the values measured by the accelerometers are corrected for roll angle effects before being used in analyses) since the Phase II testing was performed. Second, 0.6 g was only slightly below the maximum achievable lateral acceleration of some of the Phase II test vehicles. Figure 6.6 illustrates this second point with Chevrolet Astro data. As this graph shows, the Astro barely exceeded 0.6 g. As a result, the handwheel angle for the Astro (142 degrees) is determined from a portion of the lateral acceleration curve that is heavily influenced by noise.

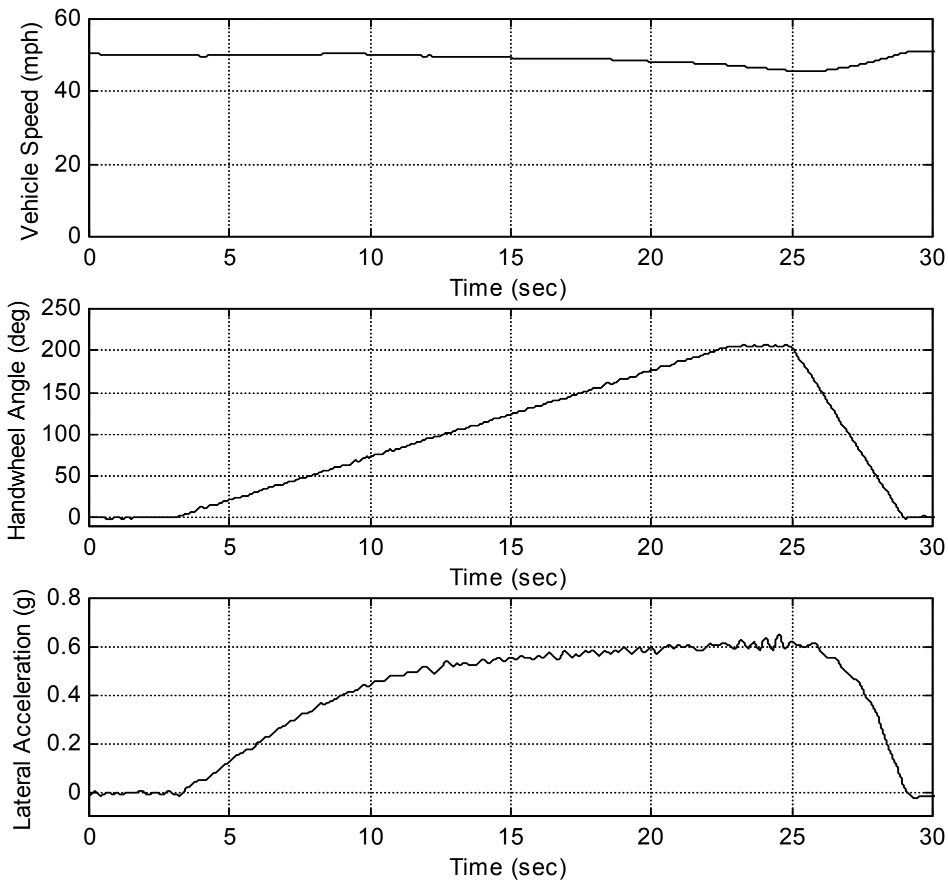

Figure 6.6. Vehicle speed, handwheel angle, and lateral acceleration of a Slowly Increasing Steer test performed with Chevrolet Astro in Phase II.

6.3.5 Use of Handwheel Position at 0.3 g

The use of handwheel inputs obtained from a lateral acceleration of 0.3 g in the Slowly Increasing Steer maneuver will now be explored. The lateral acceleration to handwheel position relationship was linear for each Phase II and IV vehicle about 0.3 g. This allowed a simple linear regression line to describe the data from 0.1 to 0.4 g. Furthermore, stability control intervention was not observed at 0.3 g for the Phase IV Toyota 4Runner or Mercedes ML320. Table 6.5 presents the handwheel magnitude data observed when lateral acceleration was at 0.3 g for all Phase II and IV vehicles. For each vehicle, ranges, averages, and standard deviations are provided.

First, consider only the Phase IV test vehicles. In agreement with the previous section, handwheel angles at 0.3 g were more repeatable than those based directly on maximum lateral acceleration. As a percentage of the mean, the average handwheel variability (as quantified by the standard deviation) for the 0.3 g lateral acceleration data for these four vehicles was 5.4 percent versus 4.2 percent for those collected at a lateral acceleration of 0.6 g, 5.2 percent for those collected at 75 percent of maximum lateral acceleration, and 10.4 percent for those collected at maximum lateral acceleration.

Table 6.5. Handwheel Angles at 0.3 g Lateral Acceleration.

Fleet	Vehicle	Left Steer (degrees)			Right Steer (degrees)			Overall (degrees)		
		Range	Ave	Std Dev	Range	Ave	Std Dev	Ave	Std Dev	Std Dev (%)
Phase II	Lumina	37 – 39	38	1.0	43 – 45	44	1.2	**41**	**3.3**	**8.0**
	Metro	36 – 37	37	0.3	38 – 40	39	0.9	**38**	**1.3**	**3.5**
	Neon	22 – 33	32	0.7	35 – 38	37	1.2	**34**	**2.5**	**7.3**
	C1500	42 – 44	43	0.5	44 – 47	45	1.6	**44**	**1.7**	**3.9**
	S-10	36- 38	37	1.0	38 – 46	42	2.3	**40**	**3.2**	**8.0**
	Ranger	43 – 47	45	3.8	51 – 55	53	1.1	**50**	**4.3**	**8.5**
	Tahoe	42 –44	43	1.2	43 – 49	46	3.2	**44**	**3.0**	**6.8**
	Tracker	38 – 40	39	1.2	39 – 40	40	0.7	**39**	**1.0**	**2.6**
	Explorer	35 – 36	36	0.6	32 – 34	33	1.2	**34**	**1.5**	**4.4**
	Astro	44 – 46	45	1.5	48 – 50	49	1.3	**47**	**2.3**	**4.9**
	Caravan	38 – 41	40	1.7	39 – 42	41	1.7	**40**	**1.5**	**3.7**
	E150	42 – 46	44	2.4	44 – 50	47	2.9	**45**	**3.1**	**6.8**
Phase IV	Blazer	45 – 48	46	1.2	52 – 55	54	1.4	**50**	**4.3**	**8.6**
	4Runner	43 – 44	44	0.3	43 – 46	45	1.8	**44**	**1.4**	**3.2**
	ML320	35 – 38	37	1.7	41	41	0.2	**39**	**2.5**	**6.5**
	Escape	36	36	0.2	34 – 37	36	1.7	**36**	**1.1**	**3.1**

Now consider both the Phase II and Phase IV data. As a percentage of the mean, the average handwheel variability for the 0.3 g lateral acceleration data for all 16 vehicles was 5.6 percent versus 7.1 percent versus for those collected at a lateral acceleration of 0.6 g. The authors believe the handwheel angles at 0.3 g to be the most repeatable of any lateral acceleration considered. This is because a lateral acceleration of 0.3 g should be in the linear range for all light vehicles, well away from the limit where noise can strongly influence the results. Since we want to minimize the variability for the handwheel inputs used to define subsequent maneuvers, the authors decided to use the handwheel angles corresponding to a lateral acceleration of 0.3 g.

6.4 Steering for the NHTSA J-Turn and Fishhooks 1a and 1b

6.4.1 Fishhook 1a and 1b Handwheel Magnitude Determination

As described in [6], Phase II Fishhook 1 handwheel inputs were comprised of a 270 degree initial steer, a 250 ms pause, and a reversal to 600 degrees in the opposite direction. The handwheel magnitudes and dwell times remained constant for all vehicles. To calculate the most appropriate handwheel *rates* for a particular vehicle, the roll angle natural frequency of that vehicle (determined during Phase II frequency response measurement testing) was used. Unfortunately, only the Ford Ranger produced discernable roll angle resonance (at 0.8 Hz). The roll angle frequency response of all other Phase II vehicles was flat. For these vehicles, a 0.5 Hz input was used for handwheel rate calculations. Fishhook 1 steering inputs were therefore identical for eleven of the twelve vehicles tested. Phase IV research sought to improve this procedure.

The fact that the Phase II methodology was unable to relate handwheel rates to vehicle responses for 92 percent of the fleet tested was undesirable. Also, it was surmised that the fixed 250 ms dwell time may have influenced response severity for some vehicles more than others. Finally, the handwheel reversal to 600 degrees was deemed too severe. Not only was the reversal unrepresentative of what actual drivers might input in a severe maneuver, its unnecessarily high magnitude also had an adverse effect on maneuver-induced tire wear.

Despite its shortcomings, Fishhook 1 was the most effective Phase II maneuver for evaluating tip-up propensity, producing two-wheel lift in five of the twelve vehicles tested. Phase IV fishhook development endeavored to retain this effectiveness, while also addressing and correcting Fishhook 1 deficiencies.

Two fishhook maneuvers were ultimately developed for use in Phase IV: Fishhook 1a and 1b. The two feature a number of similarities:

1. Inputs similar to those of Fishhook 1, but more vehicle-dependent.

2. Handwheel magnitudes based on those observed at 0.3 g in the Slowly Increasing Steer maneuver.

3. Identical handwheel rates for each steering ramp.

4. Equal initial steer and reversal handwheel magnitudes (i.e., during the reversal steer, the steering handwheel is brought back to zero and then turned to an equal steer angle in the opposite direction).

Only the method used to determine the time of initiation of handwheel reversals distinguished the two maneuvers. Fishhook 1a was an open-loop test whose reversals were always programmed to occur 250 ms after completion of the first handwheel ramp (fixed dwell time). Fishhook 1b was a closed-loop test whose reversal was determined with a roll rate feedback loop designed to initiate the handwheel reversal at maximum roll angle.

Of the two maneuvers, the closed-loop Fishhook 1b is considered conceptually superior to Fishhook 1a. However, while NHTSA had performed, during the Phase III research tests evaluate the effectiveness and repeatability of roll rate feedback (for which the results have been very good); research had been limited to one vehicle (the Chevrolet Tracker). Therefore, the current research included the open-loop Fishhook 1a for two reasons. First, it provided a baseline for which to compare closed-loop maneuver effectiveness. Secondly, if closed-loop fishhook repeatability was poor, then a second vehicle-dependent (i.e., a maneuver comprised of vehicle-specific handwheel magnitudes) alternative would be available.

To determine the scalar used by Fishhooks 1a and 1b to multiply the handwheel angles at a lateral acceleration of 0.3 g, the Phase II data was analyzed. The handwheel angles of each vehicle at 0.3 g were determined by fitting a linear regression line from 0.1 to 0.4 g and then calculating the value at 0.3 g. These angles have already been presented in Table 6.5. Although lateral acceleration data were typically very clean through 0.3 g, calculating handwheel magnitudes via linear regression prevented any anomalous noise in the data from influencing subsequent calculations. Figure 6.7 compares actual data with its regression line for the Chevrolet Tahoe.

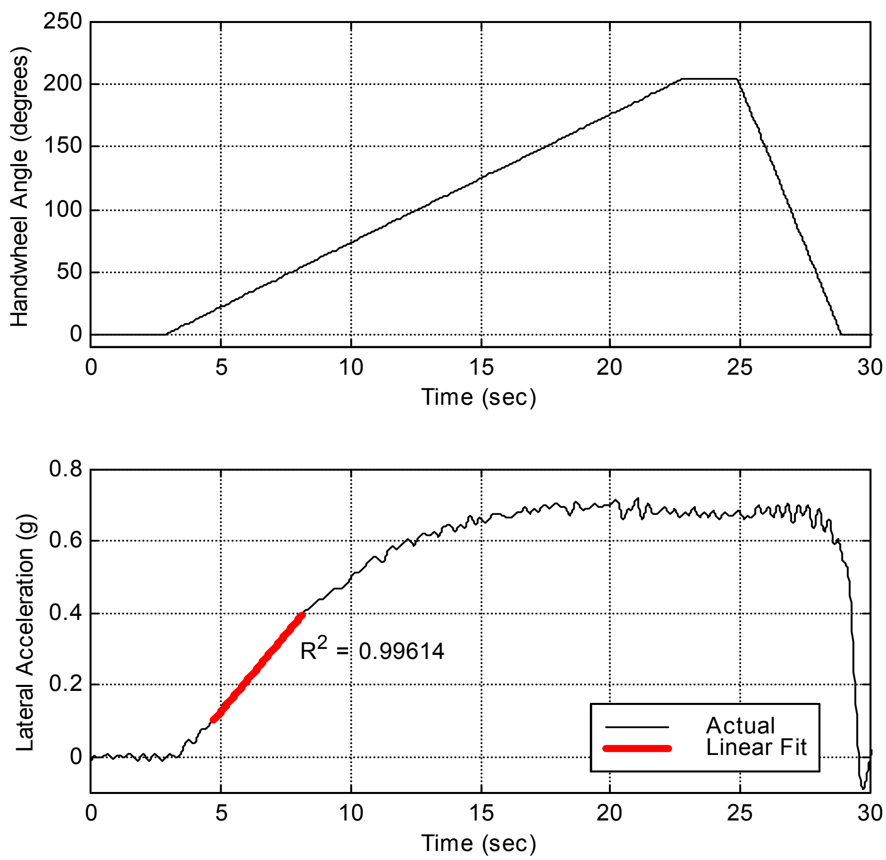

Figure 6.7. Phase II Chevrolet Tahoe handwheel angle and lateral acceleration data. The linear range used to define the lateral acceleration regression line is highlighted.

To approximate the handwheel magnitude severity of the Phase II Fishhook 1 maneuver, the authors decided that the average handwheel magnitude used for the initial steer of the Phase IV Fishhooks would be 270 degrees. Dividing the 270 degree target by the average Phase II handwheel angles at 0.3 g and rounding to the nearest tenth, a multiplier of 6.5 was computed. Table 6.6 presents the overall handwheel angle observed at 0.3 g multiplied by 6.5 for each

Phase II and IV vehicle. Also included in Table 6.6 are handwheel angles corresponding to maximum overall lateral accelerations.

As Table 6.6 shows, for all of the Phase II and Phase IV vehicles except the Ford Escape, the steering angle calculated for the initial and reversal angles for Fishhooks 1a and 1b exceeded the angle at which the maximum lateral acceleration occurred (Note: Due to the previously discussed problems in determining maximum lateral acceleration during the Phase II testing, the Phase II Maximum Lateral Acceleration Angles may not be correct.) For the Ford Escape, the initial and reversal angles for Fishhooks 1a and 1b approximately equal the angle at which the maximum lateral acceleration occurred. This is as desired since we want the fishhook's steering to saturate the tires.

Table 6.6. Fishhook and NHTSA J-Turn Handwheel Angles Calculated Using the Phase IV Methodology.

Fleet	Vehicle	Maximum Lateral Acceleration Angle (degrees)	Fishhook Angle 6.5 * $2_{0.3\ g}$		NHTSA J-Turn Angle 8.0 * $2_{0.3\ g}$	
			(degrees)	Difference from Max (%)	(degrees)	Difference from Max (%)
Phase 2	Lumina	194	269	38.3	330	70.1
	Metro	173	244	41.3	300	73.8
	Neon	189	224	18.6	275	46.0
	C1500	191	285	49.4	350	83.8
	S-10	196	261	32.9	321	63.5
	Ranger	195	328	68.4	403	107.3
	Tahoe	186	287	54.0	353	89.5
	Tracker	184	254	38.4	313	70.3
	Explorer	192	224	16.8	275	43.7
	Astro	199	306	54.0	377	89.5
	Caravan	170	263	54.6	323	90.2
	E150	198	295	48.5	362	82.8
Phase 2 Average		**189**	**270**	**42.9**	**332**	**75.9**
Phase 4	Blazer	263	326[2]	23.9	401[3]	52.5
	4Runner	161	287[2]	78.9	354[3]	120.2
	ML320	199	252[2]	26.7	310[3]	55.9
	Escape	242	233[2]	-3.6	287[3]	18.7
Phase 4 Average		**216**	**275**	**31.5**	**338**	**61.8**
Overall Average		**196**	**271**	**40.1**	**333**	**72.4**

[1]Handwheel magnitude may not actually correspond to those producing maximum lateral acceleration (as explained at the beginning of Section 6.2).

[2]Handwheel magnitudes used during Phase IV Fishhook 1a and 1b testing.

[3]Handwheel magnitudes used during Phase IV J-Turn testing.

6.4.2 Fishhook 1a and 1b Handwheel Rate Determination

In Phase II, Fishhook 1 handwheel rates were intended to be based on each vehicle's roll angle natural frequency. However, roll angle frequency response was flat for eleven of the twelve Phase II vehicles. By using an assumed value of 0.5 Hz for every vehicle for which a roll angle resonance peak was not observed, the handwheel rates were calculated to be 720 degrees per second (one-quarter of the inverse of the roll angle natural frequency).

As previously mentioned, the Phase II Fishhook 1 has been proven to be an effective maneuver for assessing dynamic rollover propensity, despite its unintended use of universal handwheel magnitudes. It is likely that some of this effectiveness is the result of the 720 degree per second steering rate. For this reason, both Phase IV fishhooks used this fixed rate exclusively. In other words, maneuver severity was based on vehicle-dependent handwheel magnitudes (and vehicle-dependent reversal timings in the case of Fishhook 1b) rather than on vehicle-specific handwheel rates.

6.4.3 J-Turn Handwheel Magnitude Determination

The J-Turn maneuver produced one of two instances of major two-wheel lift Phase II. This maneuver was comprised of a 330 degree step steer applied at 1000 degrees per second. The objective of Phase IV J-Turn development was to preserve maneuver severity while applying vehicle-specific steering inputs. Handwheel magnitudes of the NHTSA J-Turns used in Phase IV were computed in a manner identical to that used for Fishhook 1a and 1b, except that the scalar differed. In accordance with the handwheel magnitude of the Phase II J-Turn, the authors decided that the average handwheel magnitude used for the initial steer of the Phase IV J-Turn would be 330 degrees. By dividing the 330 degree target by the Phase II handwheel magnitudes at 0.3 g and rounding to the nearest tenth, a multiplier of 8.0 was computed. Table 6.6 presents the overall handwheel angle observed at 0.3 g multiplied by 8.0 for each Phase II and IV vehicle.

As Table 6.6 shows, for all of the Phase II and Phase IV vehicles, the steering angle calculated for the initial steer angle for the NHTSA J-Turn substantially exceeded the angle at which the maximum lateral acceleration occurred. The Ford Escape was closest; for this vehicle the NHTSA J-Turn steering angle exceeded the angle at which the maximum lateral acceleration occurred by 18.7 percent. This was desired since the authors wanted the NHTSA J-Turn's steering to go well beyond that required to saturate the tires.

6.4.4 J-Turn Handwheel Rate Determination

The handwheel rate used to define the NHTSA J-Turn inputs was 1000 degrees per second, identical to that used by the Phase II J-Turn. As with the Phase IV fishhooks, NHTSA J-Turn maneuver severity was based on vehicle-dependent handwheel magnitudes and not on vehicle-specific handwheel rates.

7.0 NHTSA J-TURN

The J-Turn was one of four open-loop Rollover Resistance maneuvers used in Phase IV[1]. It was derived from that used during Phase II; however, as described in Chapter 6, steering inputs were based on the handwheel position at 0.3 g in the Slowly Increasing Steer maneuver. Like the other open-loop Rollover Resistance maneuvers, the J-Turn maneuver used automated steering inputs commanded by the programmable steering machine.

This chapter is comprised of seven sections. Section 7.1 describes the maneuver and how it was executed. Section 7.2 and 7.3 discuss the steering and vehicle speed input repeatability, respectively. Section 7.4 discusses entrance speed variability. Section 7.5 discusses output repeatability. Section 7.6 presents test results. Section 7.7 is an evaluation of this maneuver based upon the evaluation factors listed in Chapter 2.

7.1 NHTSA J-Turn Maneuver Description

To begin this maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at target speed, input the handwheel commands described in Figure 7.1. Following completion of the handwheel ramp, handwheel position was maintained for four seconds. The handwheel was then returned to zero.

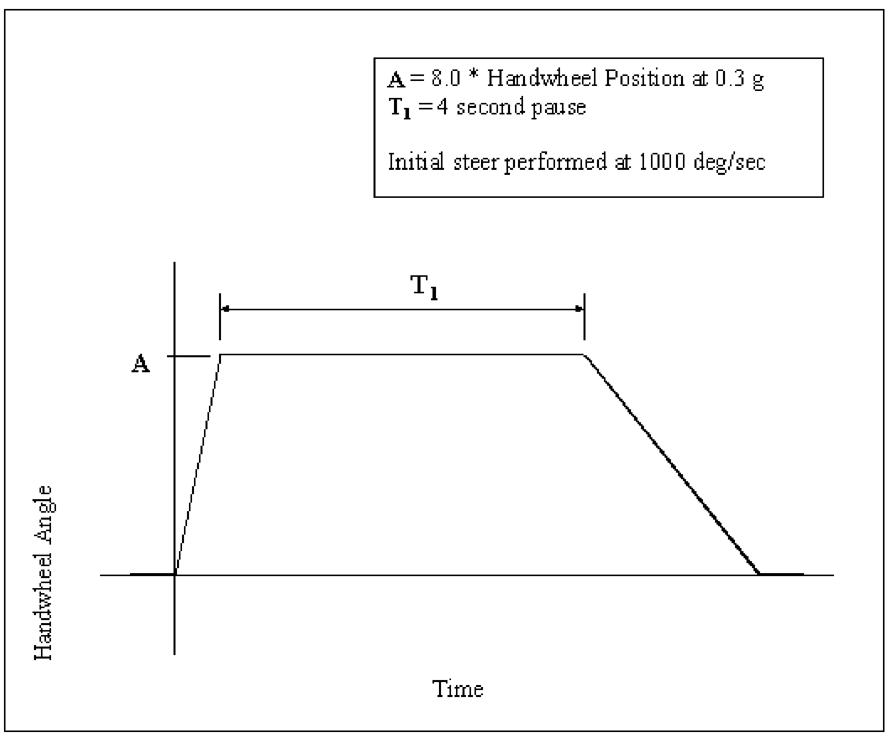

Figure 7.1. J-Turn maneuver description.

[1] These maneuvers include the J-Turn, Fishhook 1a, the Nissan Fishhook, and the Open-Loop Pseudo Double Lane Change. Fishhook 1b was a closed-loop maneuver (the control loop of Fishhook 1b was closed by the steering machine).

J-Turn handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the Slowly Increasing Steer maneuver (at 50 mph) by a scalar of 8.0. The handwheel rate of the handwheel ramp was 1000 degrees per second. Table 7.1 presents the J-Turn handwheel inputs used in Phase IV.

Table 7.1. Phase IV J-Turn Handwheel Input Magnitudes.

Vehicle	Phase IV J-Turn Handwheel Inputs[1] (degrees)		
	Nominal	**Reduced Rollover Resistance**	**Modified Handling**
Chevrolet Blazer	401	401	345
Toyota 4Runner (enabled and disabled stability control)	354	354	316
Mercedes ML320 (enabled and disabled stability control)	310	310	342
Ford Escape	287	287	267

[1]All Phase IV J-Turns used handwheel rates of 1000 deg/sec.

J-Turn tests were performed with two directions of steer, to the left and to the right. Vehicle speed was increased in 5 mph increments from 35 to 60 mph, unless at least two inches of simultaneous two-wheel lift was observed. If such wheel lift was detected, entrance speeds were iteratively reduced by 1 mph until it was no longer apparent. For vehicles with stability control, tests were performed with the stability control enabled and disabled.

7.2 NHTSA J-Turn Steering Input Repeatability

Because maneuver entrance speed was used as a severity metric for the J-Turn maneuver, a number of speed iterations were typically performed before a termination condition was realized. The handwheel inputs remained constant throughout this iterative process, thus providing an opportunity for repeatability assessment. Figure 7.2 presents these data for the Chevrolet Blazer. Each of the six right-steer tests performed in the Nominal Load configuration is represented. The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the individual tests from each other. Note that the ripples immediately after the first handwheel ramp were due to a combination of factors, including the filter applied to the data during post-processing and a slight steering machine input overshoot.

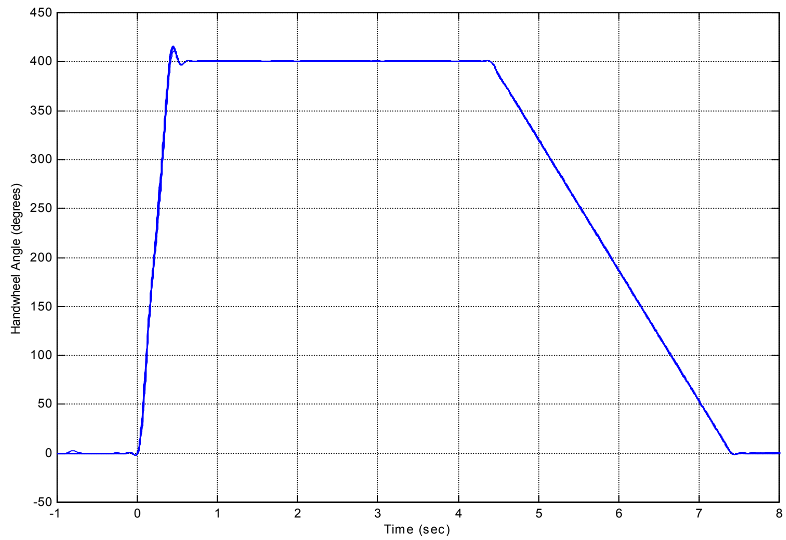

Figure 7.2. Handwheel inputs recorded during six Chevrolet Blazer J-Turns.

7.3 NHTSA J-Turn Vehicle Speed Repeatability

Figure 7.3 presents handwheel position and vehicle speed data for four J-Turns performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration. The data were collected during tests performed at 59.4, 58.1, and 58.6 mph with disabled stability control. In this configuration, only one comparable test was performed with stability control, at 58.2 mph. As seen in the figure, stability control intervention was observed 35 ms before completion of the steering input. Note, however, that vehicle speeds with enabled and disabled stability control were quite similar for many of the test runs.

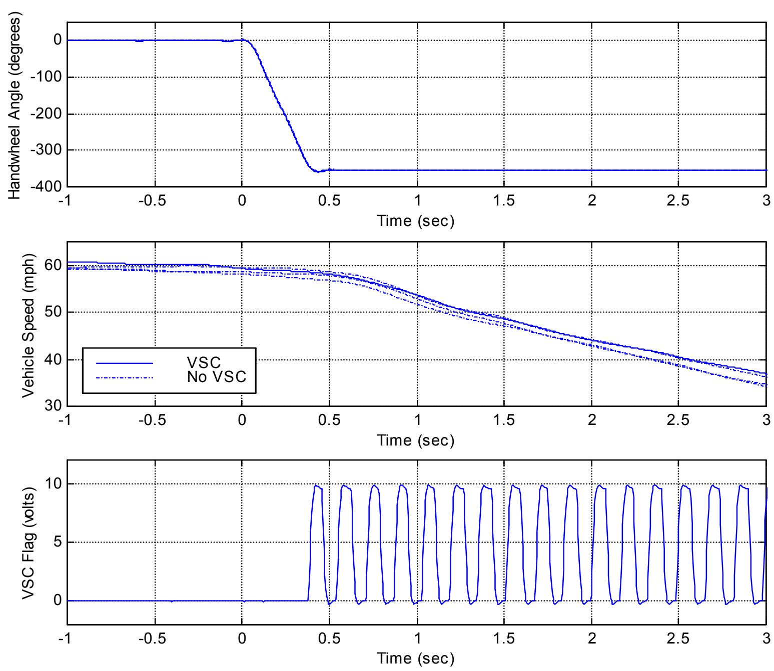

Figure 7.3. Handwheel angle, vehicle speed, and stability control intervention data recorded during four Toyota 4Runner J-Turns. The VSC Flag signal cycles during stability control intervention, and has rounded transitions due to filtering of the data.

When the handwheel was returned to zero degrees following completion of the maneuver (not pictured in Figure 7.3), the vehicle speed with enabled stability control test shown in Figure 7.3 was 21.2 mph, 64 percent lower than the 58.2 mph entrance speed. When stability control was disabled, the average vehicle speed for the Figure 7.3 tests was 18.1 mph, 69 percent lower than the 58.7 mph average entrance speed.

7.4 NHTSA J-Turn Entrance Speed Variability

When all valid J-Turn tests were considered, for all vehicles in all configurations, the driver was able to achieve entrance speeds within ±2.8 mph (4.9 percent) of the desired target speed. The actual and target maneuver entrance speed differed by an average of ±0.9 mph (1.9 percent) overall. J-Turn entrance speed variability was in agreement with that observed for the other maneuvers performed with the steering machine.

7.5 NHTSA J-Turn Output Repeatability

The severity metric used for the J-Turn maneuver was maneuver entrance speed. Since, in general, multiple tests were not run at the same maneuver entrance speed, data available for the assessment of test output repeatability was limited. If a test produced at least two inches of simultaneous two-wheel lift during a particular test series, entrance speed was iteratively decreased in approximately 1 mph increments. In some cases, the downward iteration resulted in entrance speeds nearly equal to those used in the upward iterations prior to the occurrence of two-wheel lift. If this occurred, test output repeatability could be assessed.

Figure 7.4 presents test outputs for three J-Turns performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration. The data were collected during tests 777, 778, and 779 using entrance speeds of 59.4, 58.1, and 58.6 mph, respectively. Each test in this series was performed with enabled stability control. As seen in the figure, output repeatability was very good. Also noteworthy is how repeatable the stability control intervention was found to be. The application and modulation of brake line pressures during each test were very consistent.

Data from these runs were typical of the authors' experience with the maneuver with one exception. For runs that either result in two-wheel lift or are very near to the point at which it first occurs, the roll angle repeatability can be much worse. This was the case for all rollover resistance maneuvers that induce tip up, as small fluctuations in test performance can lead to large changes in roll angle. This results in a variability of approximately ±2 mph in determining the lowest speed at which two-wheel lift occurs.

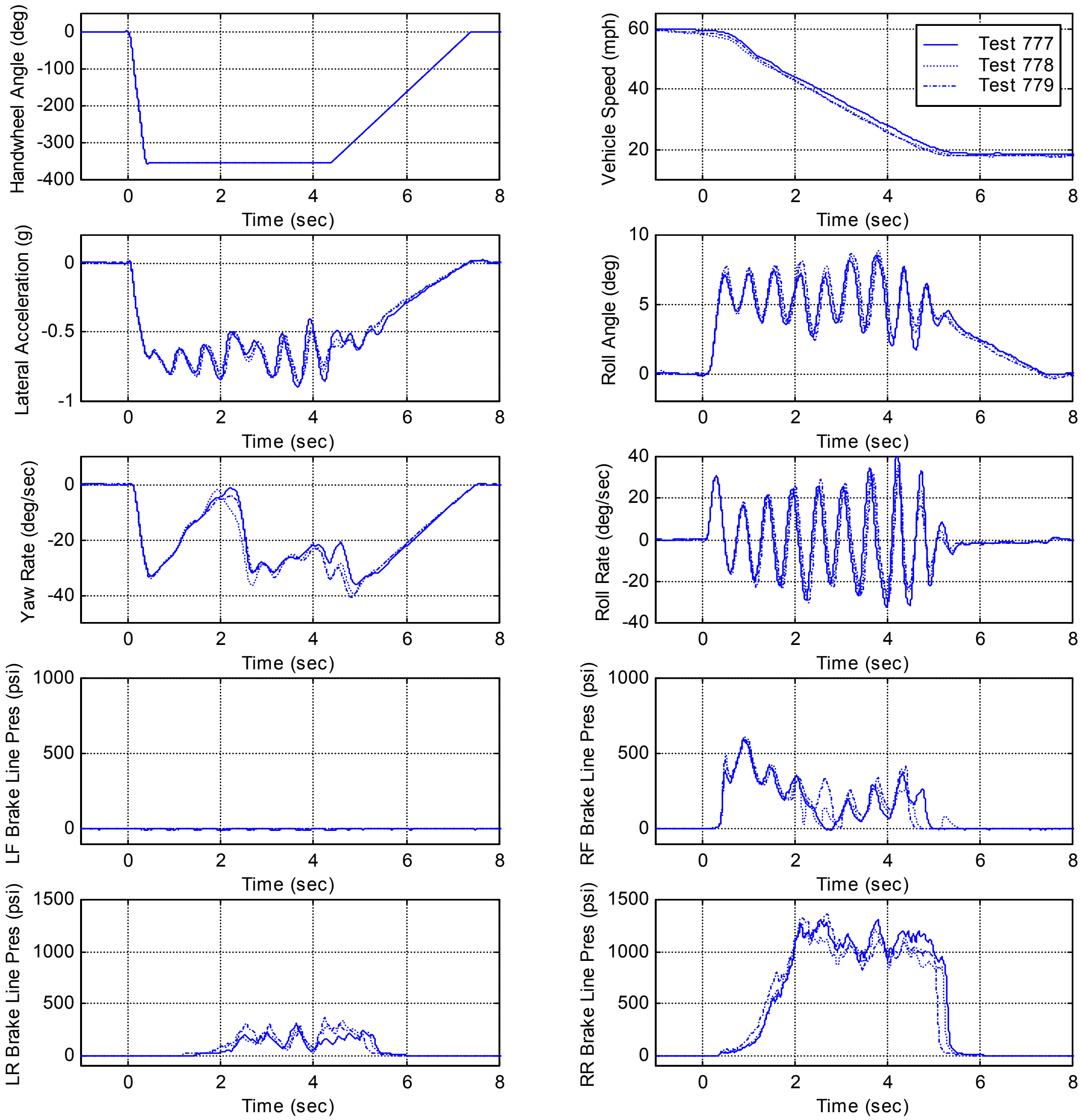

Figure 7.4. J-Turn input and output comparison of three Toyota 4Runner tests performed with enabled stability control in the Reduced Rollover Resistance configuration.

7.6 NHTSA J-Turn Results

7.6.1 Two-Wheel Lift

Although the handwheel angles and rates used for this maneuver were the larger than for Fishhooks 1a and 1b, fewer two-wheel lifts were produced. This was because no handwheel reversals were used. Table 7.2 summarizes the two-wheel lifts for J-Turns performed in the Nominal Load and Reduced Rollover Resistance configurations. The J-Turn maneuver was not performed for the Modified Handling configuration.

Table 7.2. J-Turn Two-Wheel Lift Summary.

Vehicle	Stability Control Status	Configuration			
		Nominal		Reduced Rollover Resistance	
		Left Steer (mph)	Right Steer (mph)	Left Steer (mph)	Right Steer (mph)
2001 Chevrolet Blazer	N/A	None (Max Speed = 60.9)	None (Max Speed = 62.3)	41.2	38.9
2001 Toyota 4Runner	Enabled	None (Max Speed = 58.2)	None (Max Speed = 59.3)	None (Max Speed = 59.4)	None (Max Speed = 59.5)
	Disabled	None (Max Speed = 60.4)	None (Max Speed = 60.4)	54.0	46.1
1999 Mercedes ML320	Enabled	None (Max Speed = 58.4)	None (Max Speed = 59.9)	50.9	51.7
	Disabled	None (Max Speed = 58.6)	None (Max Speed = 58.7)	45.8	45.1
2001 Ford Escape	N/A	None (Max Speed = 60.6)	None (Max Speed = 59.5)	None (Max Speed = 60.4)	None (Max Speed = 58.8)

7.6.1.1 Nominal Load

No instances of two-wheel lift were observed during Phase IV J-Turn tests performed in the Nominal Load configuration. Each vehicle was tested up to the maximum nominal test speed of 60 mph.

7.6.1.2 Reduced Rollover Resistance

With the exception of the Toyota 4Runner with enabled stability control and the Ford Escape, the addition of the roof-mounted ballast to achieve the Reduced Rollover Resistance configuration significantly increased each vehicle's dynamic rollover propensity (indicated by the occurrence of two-wheel lift). The Chevrolet Blazer was affected to the greatest extent. When evaluated in the Nominal Load configuration, left and right steer J-Turns were performed at 60.9 and 62.3 mph, respectively, without any two-wheel lift. In the Reduced Rollover Resistance configuration, two-wheel lift was produced with left and right steer J-Turns performed at 41.2 and 38.9 mph, respectively.

No two-wheel lift was produced during J-Turns performed with the Toyota 4Runner when stability control was enabled. This was in agreement with Nominal Load configuration results. When stability control was disabled in the Reduced Rollover Resistance configuration, however, two-wheel lift was produced during left and right steer tests performed at 54.0 and 46.1 mph, respectively. These speeds were both lower than the maximum entrance speeds used in the Nominal Load configuration that did not produce two-wheel lift (59.4 mph when left steering was used, 59.5 mph with right steering).

When the Mercedes ML320 was evaluated in the Nominal Load configuration with disabled stability control, left and right steer J-Turns were performed at 58.6 and 58.7 mph, respectively, without producing two-wheel lift. However, in the Reduced Rollover Resistance configuration two-wheel lift was produced when left and right steering were input at 45.8 and 45.1 mph, respectively.

A similar trend was found for the Mercedes ML320 with enabled stability control, although the increase in rollover propensity from the Nominal Load to Reduced Rollover Resistance configurations was less. In the Nominal Load configuration, left and right steer J-Turns were performed at 58.4 and 59.9 mph, respectively, without producing two-wheel. However, in the Reduced Rollover Resistance configuration, two-wheel lift was produced when left and right steering were input at 50.9 and 51.7 mph, respectively.

No two-wheel lift was produced during any J-Turn performed with the Ford Escape in the Reduced Rollover Resistance configuration. This was in agreement with Nominal Load configuration results.

7.6.2 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact were observed during J-Turn testing, regardless of vehicle configuration or occurrence of two-wheel lift.

7.6.3 Effect of Stability Control

All instances of two-wheel lift during the J-Turn maneuver occurred in the Reduced Rollover Resistance configuration. In the case of the 4Runner, no two-wheel lift was detected when stability control was enabled. When it was disabled, two-wheel lift was observed for both directions of steering.

Tests performed in the Reduced Rollover Resistance configuration with the Mercedes ML320 produced two-wheel lift with enabled and disabled stability control, regardless of the direction of steer. The entrance speeds for which two-wheel lift was observed were lower with disabled stability control, regardless of the direction of steer.

Figure 7.5 shows three left-steer J-Turns performed with the Mercedes ML320 in the Reduced Rollover Resistance configuration, one with disable stability control and two with it enabled. The maneuver entrance speed for the test with disabled stability control was 45.8 mph. This test produced two-wheel lift. The tests performed with enabled stability control began at 46.0 and 50.9 mph. The test performed at 46.0 did not produce two-wheel lift; it is included to demonstrate how stability control affected vehicle response at a speed nearly equal to that for which two-wheel lift did occur with disabled stability control. The 50.9 mph entrance speed was the lowest speed for which two-wheel lift was observed when left steering was input with enabled stability control.

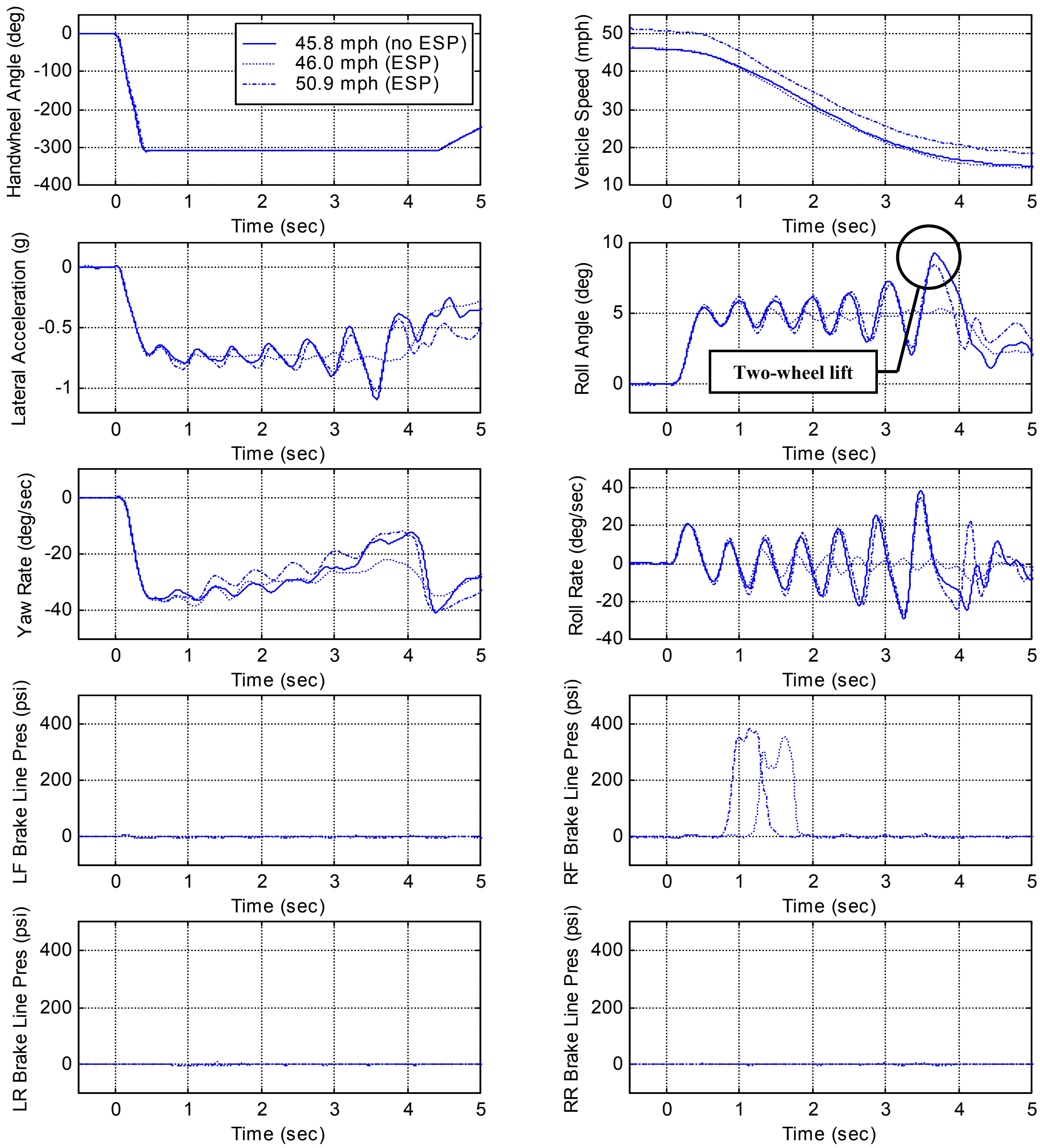

Figure 7.5. J-Turn input and output comparison for Mercedes ML320 tests performed with enabled and disabled stability control in the Reduced Rollover Resistance configuration.

For the tests shown in Figure 7.5, stability control intervention was detected during both tests for which it was enabled. In each case, the brake torque was applied to the right front of the vehicle in an attempt to correct what the stability control system interpreted as excessive oversteer configurations.

For the test performed at 46.0 mph, the braking occurred 1.1 seconds after the steering input began, and lasted approximately 0.71 seconds. This intervention had the effect of dampening the roll motion of the vehicle. Vehicle speed and yaw rate are nearly indistinguishable from those observed when stability control was disabled.

When an entrance speed of 50.9 mph was used with enabled stability control, right front braking occurred 0.77 seconds after the steering input began, and lasted approximately 0.75 seconds. Although this intervention began earlier than that observed during the test performed at 46.0 mph, it was unable to effectively dampen the roll motion of the vehicle. Local lateral acceleration and roll angle peaks increased with each oscillation until two-wheel lift was produced (after the seventh oscillation). Vehicle speed decreased in a similar manner to that of the 45.8 mph test with disabled stability control and the 46.0 mph test performed with enabled stability control.

The yaw rate of the test performed at 50.9 mph with enabled stability control decreased more rapidly than either test performed at (or near) 46 mph until approximately 3.5 seconds after the maneuver began. After that time, the yaw rate responses of the 50.9 mph test performed with enabled stability control and the 45.8 mph test performed with disabled stability control were nearly equal.

7.7 NHTSA J-Turn Maneuver Assessment

Using the evaluation factors presented in Chapter 2, the authors have rated the NHTSA J-Turn maneuver as follows:

Objectivity and Repeatability = Excellent

The NHTSA J-Turn was the most objective and repeatable of all of the Rollover Resistance maneuvers performed during Phase IV. By using the programmable steering machine, handwheel inputs were precisely executed, and repeatably replicated from run-to-run. Test drivers were able to achieve maneuver entrance speeds within an average of ± 0.9 mph (1.9 percent) from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data observed during J-Turn tests were highly repeatable. That said, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, lower than that observed at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of the J-Turn maneuver.

Performability = Excellent

The NHTSA J-Turn had only a single major steering input. As such, it was easiest of all of the dynamic rollover propensity maneuvers to perform. Objective and repeatable NHTSA J-Turns were easily performed using the programmable steering controller. The test procedure was well developed. Procedures have been developed to adapt the NHTSA J-Turn maneuver to the characteristics of the vehicle being tested.

Discriminatory Capability = Excellent
(when limited to vehicles with low rollover resistance and/or disadvantageous load condition)

None of the Phase IV test vehicles experienced two-wheel lift during NHTSA J-Turn tests performed in the Nominal configuration. . However, all of the vehicles except the Ford Escape and the Toyota 4Runner with its yaw stability control enabled did have two-wheel lift when tested in their Reduced Rollover Resistance configuration.

The NHTSA J-Turn is not a severe enough maneuver to discriminate between typical, current generation, sport utility vehicles loaded with a driver and passenger only (Phase IV vehicles in the Nominal Load configuration). However, it was sensitive to the decrease in rollover resistance attributable to a decrease in SSF of 0.05. Also the speed at tip-up could discriminate between the individual Phase IV test vehicles when the entire group was loaded to produce a decrease in SSF of 0.05. In Phase IV a roof load of either 120 or 180 pounds was used to reduce the SSF by 0.05, but the addition of 5 to 6 passengers causes a similar reduction in SSF for typical current generation SUVs, vans and pickup trucks.

Appearance of Reality = Good

Drivers perform NHTSA J-Turns during actual driving. Cloverleaf entrance/exit ramps and tightly curved roads driven at substantial speeds are two such examples. The NHTSA J-Turn was not given an excellent rating in this category, however, because it is very unlikely that actual drivers would input handwheel angles as large as those used in the J-Turn without also applying sustained braking. Braking introduces longitudinal wheel slip, and longitudinal wheel slip can greatly reduce lateral force. Since a reduction in lateral force has the effect of lowering the overturning moment of the vehicle, the likelihood of an on-road untripped rollover occurring (while the driver is engaged in sustained braking) is lessened.

During NHTSA's discussions with the automotive industry, every manufacturer stated that they routinely perform J-Turn testing during vehicle development. This maneuver has a long history of industry use.

8.0 NHTSA FISHHOOK 1A

Fishhook 1a (also called the Fixed Timing Fishhook) was one of four open-loop Rollover Resistance maneuvers used in Phase IV[1]. It was derived from the Fishhook 1 maneuver used during Phase II, however as described in Chapter 6, steering inputs were based on the handwheel position at 0.3 g in the Slowly Increasing Steer maneuver. Like the other open-loop Rollover Resistance maneuvers, the Fishhook 1a maneuver used automated steering inputs commanded by the programmable steering machine.

This chapter is comprised of seven sections. Section 8.1 describes the maneuver and how it was executed. Section 8.2 and 8.3 discuss the steering and vehicle speed input repeatability, respectively. Section 8.4 discusses maneuver entrance speed variability. Section 8.5 discusses output repeatability. Section 8.6 presents test results. Section 8.7 provides a maneuver assessment and concluding remarks.

8.1 Fishhook 1a Maneuver Description

To begin this maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at target speed, initiated the handwheel commands described in Figure 8.1. Following completion of the countersteer, handwheel position was maintained for three seconds. The handwheel was then returned to zero.

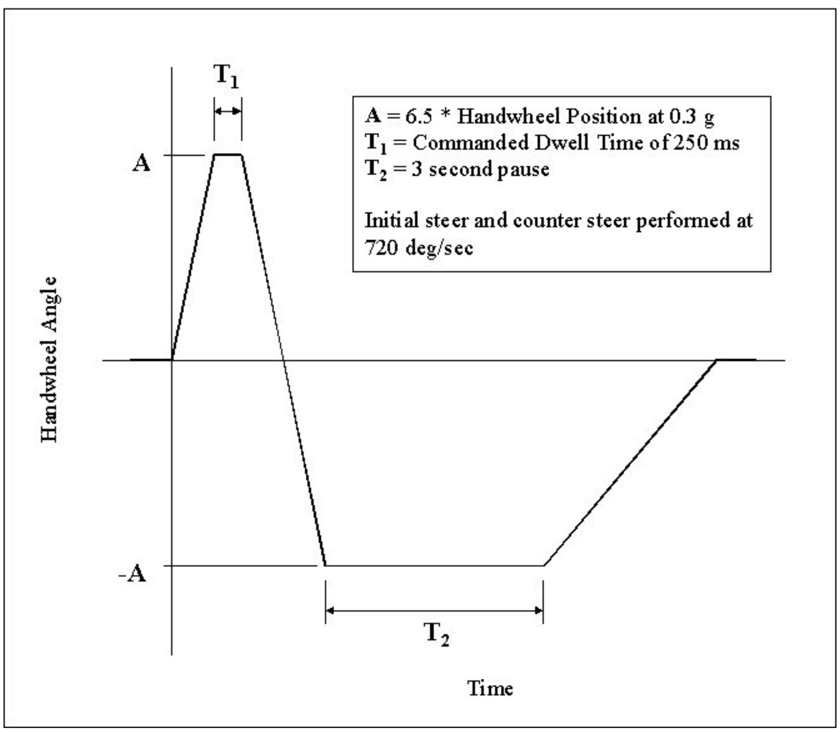

Figure 8.1. Fishhook 1a maneuver description.

[1] These maneuvers include the J-Turn, Fishhook 1a, the Nissan Fishhook, and the Open-Loop Pseudo Double Lane Change. Fishhook 1b was a closed-loop maneuver (the control loop of Fishhook 1b was closed by the steering machine).

Fishhook 1a handwheel magnitudes were calculated by multiplying the handwheel angle that produced an average of 0.3 g in the Slowly Increasing Steer maneuver (at 50 mph) by a scalar of 6.5. The commanded dwell time (the time between completion of the initial steering ramp and the initiation of the countersteer) for Fishhook 1a was 250 ms. The handwheel rates of the initial steer and countersteer ramps were 720 degrees per second. Table 8.1 presents the Fishhook 1a handwheel inputs used in Phase IV.

Table 8.1. Phase IV Fishhook 1a Maneuver Handwheel Input Magnitudes.

Vehicle	**Phase IV Fishhook 1a Handwheel Inputs[1] (degrees)**		
	Nominal Load	**Reduced Rollover Resistance**	**Modified Handling**
Chevrolet Blazer	326	326	Not Tested
Toyota 4Runner (enabled and disabled stability control)	287	287	Not Tested
Mercedes ML320 (enabled and disabled stability control)	252	Not Tested	Not Tested
Ford Escape	233	233	Not Tested

[1]All Phase IV Fishhook 1a maneuvers used handwheel rates of 720 degrees per second.

Fishhook 1a tests were performed with two initial directions of steer, to the left (referred to as left-right fishhooks) and to the right (right-left fishhooks). Vehicle speed was increased in 5 mph increments from 35 to 50 mph, unless at least two inches of simultaneous two-wheel lift was occurred. If such wheel lift was detected, entrance speeds were iteratively reduced by 1 mph until it was no longer apparent. Tests were performed with the stability control enabled and disabled.

8.2 Fishhook 1a Steering Input Repeatability

The handwheel magnitudes used to define Fishhook 1a were vehicle dependent, based on lateral acceleration data produced during Slowly Increasing Steer tests. Because maneuver entrance speed was used as a severity metric for the Fishhook 1a maneuver, a number of speed iterations were needed before a termination condition was realized. The handwheel inputs remained constant throughout this iterative process, thus providing an opportunity for repeatability assessment. Figure 8.2 presents these data for the Mercedes ML320. All six right-left steer tests performed in the Nominal Load configuration with stability control are presented. The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the individual tests from each other. Note that the ripples immediately after the first handwheel ramp, as well as immediately before and after the second handwheel ramp, were due to a combination of factors, including the filter applied to the data during post-processing and a slight steering machine input overshoot.

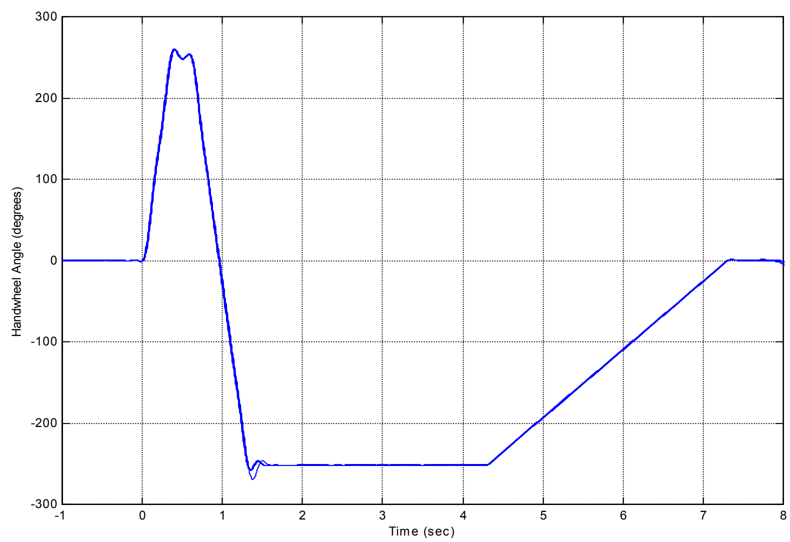

Figure 8.2. Handwheel inputs recorded during six Mercedes ML320 Fishhook 1a maneuvers.

8.3 Fishhook 1a Vehicle Speed Repeatability

Figure 8.3 shows handwheel position and vehicle speed data for four right-left Fishhook 1a tests performed with the Ford Escape in the Reduced Rollover Resistance configuration. The data were collected during tests performed at 48.9, 48.2, and 47.7 mph. When the handwheel was returned back to zero degrees following completion of the maneuver (four seconds after completion of the steering reversal), the vehicle speeds ranged from 15.4 to 18.0 mph. These speeds were 62.4 to 68.5 percent lower than the respective entrance speeds.

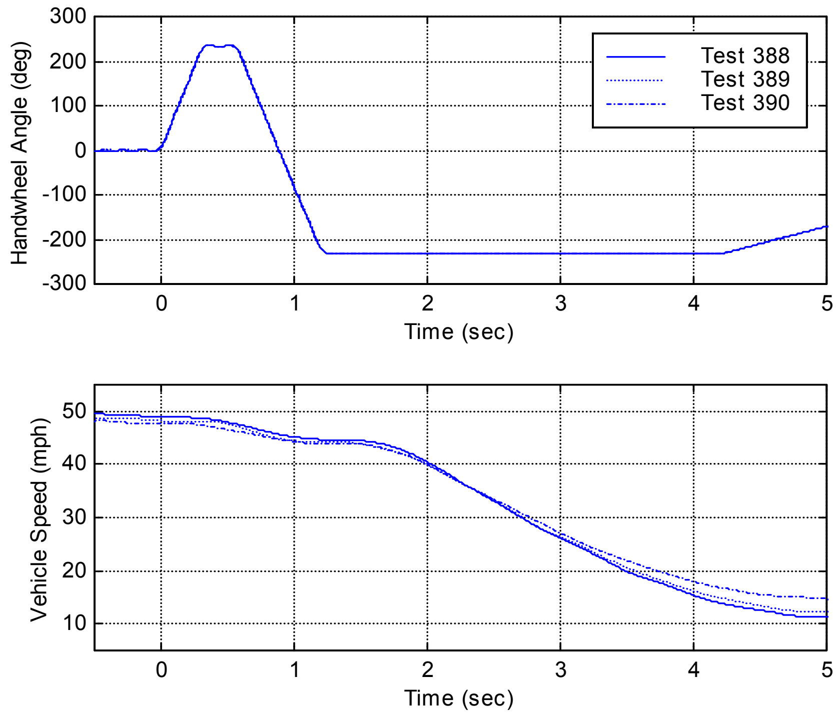

Figure 8.3. Handwheel angle and vehicle speed data for three Fishhook 1a tests performed with the Ford Escape.

8.4 Fishhook 1a Entrance Speed Variability

When all valid Fishhook 1a tests were considered, for each vehicle in all configurations, the driver was able to achieve entrance speeds within ±3.9 mph (9.3 percent) of the desired target speed. The actual and target maneuver entrance speed differed by an average of ±1.4 mph (3.3 percent) overall. Fishhook 1a entrance speed variability was in agreement with that of the other maneuvers performed with the steering machine.

8.5 Fishhook 1a Output Repeatability

The severity metric for the Fishhook 1a was maneuver entrance speed. Since, in general, multiple tests were not run at the same maneuver entrance speed, data available for the assessment of test output repeatability was limited. If a test produced at least two inches of simultaneous two-wheel lift during a particular test series, entrance speed was iteratively decreased in approximately 1 mph increments. In some cases, the downward iteration resulted in entrance speeds nearly equivalent to those used in the upward iterations prior to the occurrence of two-wheel lift. If this occurred, test output repeatability could be assessed. Figure 8.4 presents test outputs for three Fishhook 1a tests performed with the Chevrolet Blazer in the Reduced Rollover Resistance loading configuration. The data were collected during two tests performed at 37.8 mph (Tests 1464 and 1469), and a third at 37.3 mph (Test 1470).

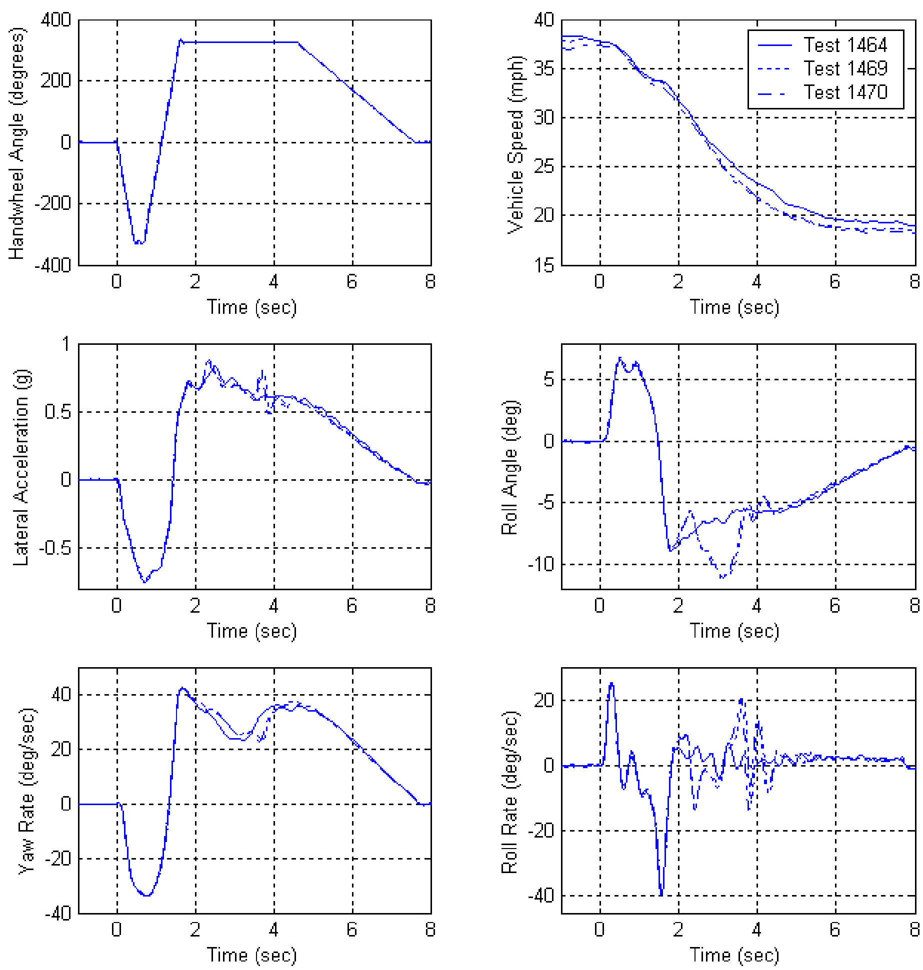

Figure 8.4. Inputs and outputs recorded during the three Chevrolet Blazer Fishhook 1a tests.

Output repeatability before the steering reversals was excellent within a particular test series, making it impossible to distinguish the individual tests from each other. Post reversal repeatability was very good, however there was evidence that if an extended number of tests were performed within a series (in an attempt to isolate the lowest speed at which at least two inches of simultaneous two-wheel lift occurred), test output repeatability could be adversely affected by tire shoulder wear.

The vehicle speed, lateral acceleration, and yaw rate traces in Figure 8.4 clearly show the very high repeatability of this maneuver. The roll angle and roll rate traces show the non-repeatability in roll angle that occurs around the point of two-wheel lift. All three of these runs had two-wheel lift approximately three seconds into the test. The amount of two-wheel lift was substantially less for one run than for the other two. However, because we are no longer differentiating between moderate and major two-wheel lifts, the differences would not affect the reported results for this maneuver.

Test 1464 was the second of ten left-right fishhooks performed in this particular test series, and produced approximately two inches of simultaneous two-wheel lift. Tests 1469 and 1470 were the seventh and eighth tests, respectively, of this test series; both produced approximately five inches of simultaneous two-wheel lift. Due to the amount of two-wheel lift produced during Tests 1469 and 1470, front and rear outrigger contact occurred. The entrance speeds of these tests differed by only 0.5 mph. The large difference between their roll angle traces occurs because near the initiation of two-wheel lift, the roll angle becomes mathematically unstable; the vehicle either falls over or it does not. As was discussed above for the NHTSA J-Turn, this roll angle non-repeatability occurs for all maneuvers that generate two-wheel lift.

Table 8.2 summarizes the ten left-right Fishhook 1a tests performed with the Chevrolet Blazer in the Reduced Rollover Resistance configuration. While the nominal series would contain test runs performed with nominal maneuver entrance speeds of 35, 40, 45, and 50 mph, the series producing Table 8.2 data contained a total of ten left-right fishhooks, including seven tests producing two inches or more of simultaneous two-wheel lift. The first occurrence of at least two inches of wheel lift was during Test 1464, second test of the series. Although the nominal entrance speed for this test would normally have been 40 mph, the test driver was uncomfortable with a five mph speed increase from the second test. As such, the experimenter decided to perform an intermediate speed test using a two mph entrance speed increment, resulting in a nominal speed of 37 mph. The actual entrance speed was 37.8 mph. Video data reduction performed at a later date revealed this test had produced two inches of simultaneous two-wheel lift, however, the in-the-field experimenter did not believe that two inches of lift had occurred, and proceeded to increase maneuver entrance speed to 40 mph.

Table 8.2. Output Summary For Left-Right Fishhook 1a Tests Performed With The Chevrolet Blazer In The Reduced Rollover Resistance Loading Configuration.

Test #	Entrance Speed (mph)		Two-Wheel Lift (inches)	Maximum Lateral Acceleration (g)		Maximum Roll Angle (deg)		Maximum Roll Rate (deg/sec)		Maximum Yaw Rate (deg/sec)	
	Nominal	Actual		Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal
1463	35	36.0	None	0.74	0.86	6.3	8.6	24.4	38.5	33.3	38.2
1464	**37**	**37.8**	**2**	**0.75**	**0.84**	**6.7**	**8.9**	**25.2**	**39.9**	**34.0**	**42.0**
1465	40	41.3	8[1]	0.74	0.78	6.6	14.6	25.7	42.5	32.6	48.1
1466	39	40.5	8[1]	0.73	0.79	6.6	14.7	25.2	42.0	32.4	46.6
1467	38	40.0	8[1]	0.73	0.82	6.6	14.7	26.0	41.6	32.3	44.9
1468	37	39.3	8[1]	0.73	0.83	6.6	14.8	25.1	41.7	33.2	46.0
1469	**36**	**37.8**	**6[2]**	**0.73**	**0.88**	**6.9**	**11.3**	**25.1**	**38.9**	**34.1**	**43.0**
1470	**35**	**37.3**	**4[2]**	**0.73**	**0.87**	**6.4**	**11.1**	**25.0**	**40.0**	**34.7**	**42.4**
1471	34	35.8	None	0.73	0.86	6.8	8.8	24.7	39.0	34.6	41.5
1472	33	34.4	None	0.72	0.81	6.3	8.2	24.0	36.7	35.1	38.8

Note: Highlighted tests were included in Figure 8.4.

[1]Additional two-wheel lift was suppressed by front and rear outrigger contact with the ground.
[2]Front and rear outrigger contact with the ground was detected; however, impact was less severe than that observed during tests 1465-1468.

The next test (1465) had a nominal entrance speed of 40 mph. This resulted in an actual entrance speed of 41.3 mph, and enough two-wheel lift to strike both front and rear outriggers. The entrance speeds of subsequent tests were then iteratively decreased in approximately one mph increments until such lift no longer occurred. This iterative process resulted in two tests being performed at 37.8 mph (Tests 1464 an 1469). The tire wear that occurred between during the four tests separating these Tests 1464 and 1469 may have been partially responsible for the different outcomes of these two tests. However, the authors believe that the main reason for these differences is that at 37.8 mph, in the Reduced Rollover Resistance configuration, the Blazer was operating at a threshold for which two-wheel lift of two inches *or more* was possible. Due to the loss of roll stability, different roll responses may occur from essentially equivalent inputs.

8.6 Fishhook 1a Results

8.6.1 Two-Wheel Lift

The Fishhook 1a maneuver was an effective open-loop maneuver for assessing the dynamic rollover propensity of the Phase IV test vehicles. Although the handwheel dwell time was held constant for all vehicles, configurations, and test speeds, conduct of the Fishhook 1a maneuver produced numerous two-wheel lifts. Table 8.3 summarizes the two-wheel lifts for Fishhook 1a tests performed for the Nominal Load and Reduced Rollover Resistance configurations. Fishhook 1a was not performed for the Modified Handling test configuration. Note that the Mercedes ML320 was not tested in the Reduced Rollover Resistance configuration due to the severity of its roll oscillations during testing in the Nominal Load configuration.

8.6.1.1 Nominal Load

Four situations resulting in two-wheel lift occurred during Phase IV Fishhook 1a tests performed in the Nominal Load configuration: one with the Chevrolet Blazer and three with the Mercedes ML320.

Although no two-wheel lift greater than or equal to two inches was produced during right-left tests with the Blazer, two-wheel lift of this magnitude *did* occur when left-right steering was input during a test performed at 40.2 mph.

The ML320 exhibited a greater rollover propensity during tests performed with disabled stability control (compared to those performed with it enabled). No two-wheel lift occurred when left-right steering was input with enabled stability control in the Nominal Load configuration. With disabled stability control, two-wheel lift occurred during a left-right steer test performed at 44.1 mph. When right-left handwheel inputs were used, with stability control, two-wheel lift first occurred at a maneuver entrance speed to 47.8 mph. With disabled stability control, right-left steering first produced two-wheel lift at a lower maneuver entrance speed of 43.5 mph.

Table 8.3. Fishhook 1a Two-Wheel Lift Summary.

Vehicle	Stability Control Status	Loading Configuration			
		Nominal Load		Reduced Rollover Resistance	
		Left-Right Steer (mph)	Right-Left Steer (mph)	Left-Right Steer (mph)	Right-Left Steer (mph)
2001 Chevrolet Blazer	N/A	40.2	None (Max Speed = 51.8)	37.3	36.2
2001 Toyota 4Runner	Enabled	None (Max Speed = 49.9)	None (Max Speed = 50.0)	47.6	None (Max Speed = 49.9)
	Disabled	None (Max Speed = 49.8)	None (Max Speed = 49.8)	40.2	38.4
1999 Mercedes ML320	Enabled	None (Max Speed = 48.5)	47.8	Not Tested	
	Disabled	44.1	43.5		
2001 Ford Escape	N/A	None (Max Speed = 49.5)	None (Max Speed = 49.5)	48.4	None (Max Speed = 48.9)

8.6.1.2 Reduced Rollover Resistance

The Reduced Rollover Resistance configuration increased each vehicle's dynamic rollover propensity. The extent of its influence varied from vehicle to vehicle.

The Chevrolet Blazer was very affected, especially for right-left steering. When tested in the Nominal Load configuration, a Fishhook 1a maneuver using right-left steering was performed at 51.8 mph without two-wheel lift. In the Reduced Rollover Resistance configuration, two-wheel lift was produced during a test performed at 36.2 mph. When left-right steering was input, the Blazer produced two-wheel during a test performed at 37.3 mph. This test had an entrance speed 2.9 mph less than that required for the Nominal Load configuration (40.2 mph) to produce two-wheel lift.

When tested in the Reduced Rollover Resistance configuration, the Toyota 4Runner exhibited a greater rollover propensity during tests performed with disabled stability control (compared to those performed with it enabled). With left-right steering and disabled stability control, a maneuver entrance speed of 40.2 mph produced two-wheel lift with the 4Runner. Enabling stability control increased the maneuver entrance speed to 47.6 mph before two-wheel lift occurred. When right-left steering was input, the effect of the 4Runner's stability control was even more pronounced. No two-wheel lift greater than to two inches was produced when stability control was enabled. With it disabled, two-wheel lift occurred during a test performed at 38.4 mph.

Two-wheel lift was produced during left-right tests performed at 48.4 mph with the Ford Escape in the Reduced Rollover Resistance configuration. No two-wheel lift was produced during right-left steer tests.

The Mercedes ML320 was not tested in the Reduced Rollover Resistance configuration due to the severity of its roll oscillations produced during tests performed in the Nominal Load configuration. Since this vehicle had two-wheel lift in the Nominal Load configuration for right left steering with stability control enabled and for both left-right and right-left steering with stability control disabled, the authors believe that two-wheel lift would have occurred for all situations if this vehicle had been tested in the Reduced Rollover configuration.

Of the Phase IV vehicles/configurations, the Ford Escape and Toyota 4Runner (with stability control enabled) were the least influenced by the Reduced Rollover Resistance configuration. Although both vehicles produced two-wheel lift during left-right Fishhook 1a tests in this configuration, it occurred when the maneuvers began very near the nominal termination speed of 50 mph. No two-wheel lift occurred for this configuration when the Escape or 4Runner were evaluated with right-left steering.

8.6.2 Tire Debeading and Rim Contact

Fishhook 1a tests produced three tire debeads during the Phase IV testing. One occurred during a test performed with the Ford Escape in the Reduced Rollover Resistance configuration. The other two occurred during Mercedes ML320 tests performed in the Nominal Load configuration with disabled stability control. Table 8.4 summarizes relevant information for each of these tests. Note that inner tubes were not being installed prior to the Fishhook 1a tests for which debeading occurred.

Table 8.4. Debeads During Fishhook 1a Testing.

Vehicle	Configuration	Stability Control Status	Entrance Speed (mph)	Direction of Steer	Inner Tube Installation	Location of Debead	Number of Tests Prior to Debead
Ford Escape	Reduced Rollover Resistance	N/A	49.7	Left-Right	None	Left Front	10
Mercedes ML320	Nominal	Disabled	48.4	Right-Left	None	Right Front	3
			44.1	Left-Right	None	Left Front	2

Figure 8.5 shows the left front wheel/tire of the Escape in its final position after the test for which the left front debead occurred. Figure 8.6 shows a similar image of the ML320.

Figure 8.5. Left front wheel/tire of the Ford Escape observed post-debead**.**

Figure 8.6. Right front wheel/tire of the Mercedes ML320 observed post-debead.

8.6.2.1 Ford Escape

Two Fishhook 1a test series were performed with the Ford Escape in the Reduced Rollover Resistance configuration. The first was comprised of eleven tests using only left-right steering. This series was not representative of how Fishhook 1a tests were typically performed, and was incomplete due to the lack of any right-left steering input. This series was terminated when a left front tire debead occurred early in a test performed at 49.7 mph. This tire debead resulted in considerable damage to the test surface (as previously shown in Figure 3.1), and its occurrence required all subsequent fishhooks performed by VRTC to be performed with innertubes. Innertubes were believed to be the simplest, most cost effect way of preventing damage to the test surface during fishhook maneuvers.

The left front tire debead of the Escape occurred after ten left-right Fishhook 1a tests had been performed. The number of tests was significantly greater than the four nominal tests specified in the "Fishhook 1a Test Procedure" section presented earlier in this report. After four tests, the experimenter noticed that the front and rear outrigger caster wheels had come in contact with the ground, however, less than one inch of simultaneous two-wheel lift had been observed during any test up to that point. Because it was uncertain as to when outrigger contact had first been made (i.e., at what maneuver entrance speed), and because the amount of possible two-wheel lift was restricted to less than two inches by the outriggers, a decision to raise the front and rear outriggers was made.

Using the same tire set as for the previous four tests, the maneuver entrance speed was iteratively increased from a nominal 35 to a nominal 45 mph in 5 mph increments. During the 45 mph test, the experimenter observed two-wheel lift, but was unsure whether two inches of simultaneous lift had been produced (the criteria to begin the downward iteration of vehicle speed). For this reason, the 45 mph test was repeated. After the second 45 mph test, the driver expressed concern about increasing maneuver entrance speed to a nominal 50 mph in one final increment. Subsequent tests were thus performed at nominal maneuver entrance speeds of 47 mph and then 50 mph. During the test performed at 50 mph, the experimenter observed two inches of two-wheel lift. Nominal maneuver entrance speed was therefore reduced by one mph, and an eleventh test using a nominal maneuver entrance speed of 49 mph was performed.

Shortly after the countersteer of the eleventh test had been completed, a left front tire debead occurred. Analysis of the data produced during this test revealed that the actual maneuver entrance speed was 49.7 mph, nearly equal to the 49.9 mph speed used one test prior to the debead. Figure 8.7 compares the lateral accelerations, roll angles, roll rates, and yaw rates of these two tests. The maximum lateral acceleration of the test performed at 49.7 mph (that produced the tire debead) was 0.94 g. This was 15 percent less than the 1.10 g produced by the test at 49.9 mph with no tire debeading. (The lateral acceleration of the 49.9 mph test had such a high maximum value (1.10 g) because of the roll oscillations of the vehicle. These oscillations can clearly be seen in Figure 8.7.)

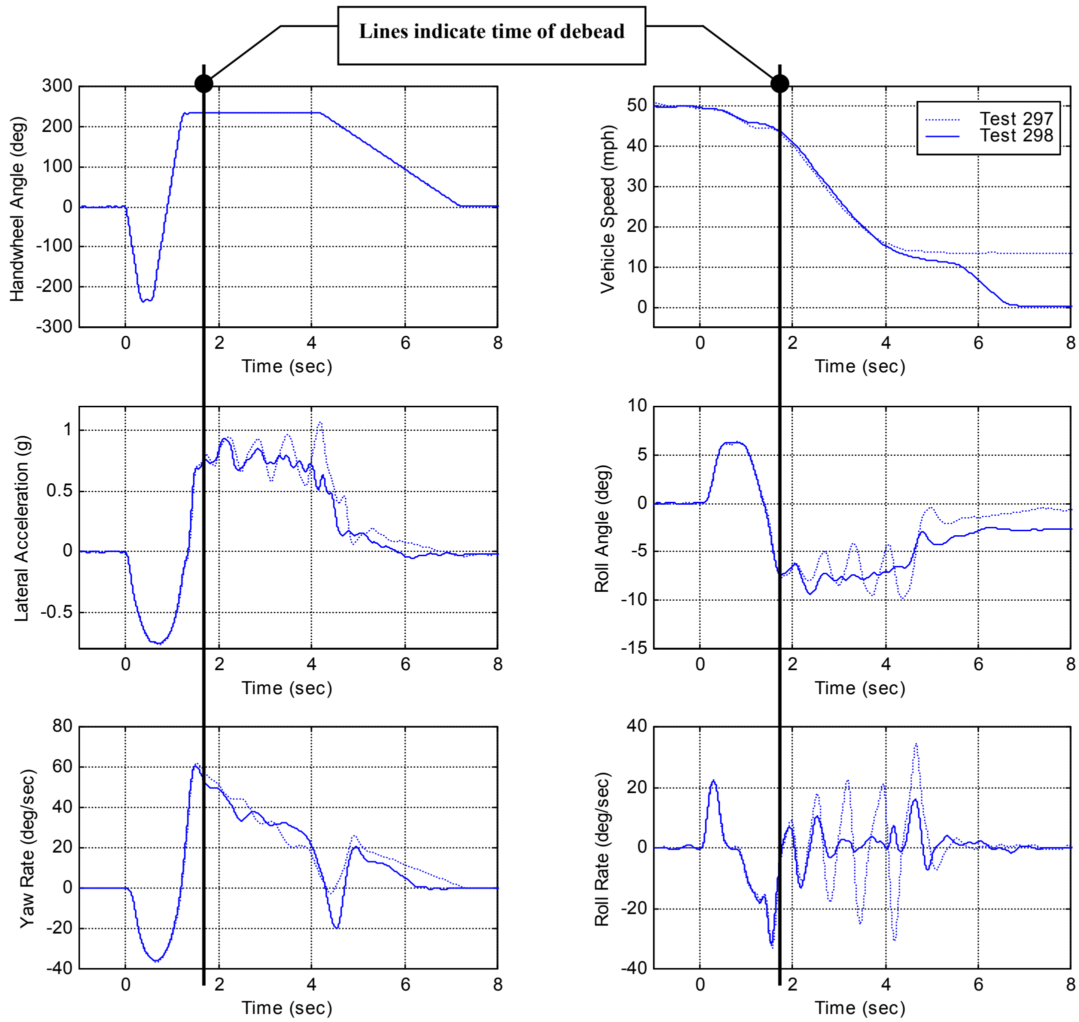

Figure 8.7. Inputs and outputs from two Fishhook 1a tests performed with the Ford Escape in the Reduced Rollover Resistance configuration. A left front tire debead was observed during Test 298.

8.6.2.2 Mercedes ML320

Fishhook 1a tests were performed with the ML320 only in the Nominal Load configuration. Testing began with right-left steering. After the first debead, the affected wheel and tire were replaced, and testing continued with left-right steering. Once the second debead occurred, the test series was terminated. No additional Fishhook 1a tests were performed (i.e., no ML320 Fishhook 1a tests were repeated with innertubes). No debeads or rim-to-pavement contact occurred during Fishhook 1a tests performed with the ML320 when stability control was enabled.

The combination of high maneuver entrance speed and Fishhook 1a handwheel inputs was found to set the ML320 into apparently negatively damped roll oscillations. As the amplitude of the roll motion increased, the lateral forces acting on the outside tires (front and rear) became very large[2]. These lateral forces caused the ML320 to achieve much greater lateral accelerations than for other Phase IV vehicles, exceeding 1.5 g during both Fishhook 1a tests that produced debeads. These forces will be discussed in Chapter 9.

8.6.3 Effect of Stability Control on Two-Wheel Lift

The Toyota 4Runner and Mercedes ML320 allowed comparisons to be made (on a per vehicle basis) between tests with enabled *and* disabled stability control. The following discussion provides lateral acceleration, yaw rate, roll angle, roll rate, and two-wheel lift comparisons between tests performed with both vehicles.

8.6.3.1 Mercedes ML320

Figure 8.8 presents three right-left Fishhook 1a maneuvers performed with the Mercedes ML320 in the Nominal Load configuration. The figure includes a test performed at 43.5 mph with disabled stability control, the lowest speed for which two-wheel lift occurred in this configuration with the ML320. The tests in this figure performed with enabled stability control had maneuver entrance speeds of 43.4 and 47.8 mph. The 47.8 mph entrance speed was the lowest for which two-wheel lift occurred with the ML320 in this configuration. The 43.4 mph test did not produce two-wheel lift. It is shown only to demonstrate how stability control affected the vehicle during a test performed with an entrance speed similar to that producing two-wheel lift with disabled stability control.

For the tests shown in Figure 8.8, stability control intervention occurred during both tests with it enabled. In each test, brake torque was applied first to the left front, then to the right front, wheel of the vehicle in an attempt to correct what the stability control system interpreted as excessive oversteer induced by the initial steer and countersteer inputs, respectively.

For the test performed at 43.4 mph, braking first occurred 1.0 second after the steering input began (0.42 seconds after the reversal was initiated), and lasted approximately 0.37 seconds. When compared to the test performed at 43.5 mph with disabled stability control, the effects of this intervention were not apparent. The second intervention occurred 1.4 seconds after the initial steer was input (0.81 seconds after the reversal began). This intervention had some effect in dampening the roll motion of the vehicle. When compared to the test performed at 43.5 mph with disabled stability control, roll oscillations were of somewhat lesser magnitude.

The most pronounced effect of the intervention that occurred during the test performed at 43.4 mph was how it affected the yaw rate of the vehicle after the steering reversal was input. The suppression of excessive yaw directly affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were made by the stability

[2] Four wheel load transducers measuring the longitudinal, lateral, and vertical forces acting on each tire (as well as the rotational, overturning, and camber moments) were installed on the Phase IV vehicles as part of research on the effects of outrigger designs on vehicle response. The findings of this study are expected to be released later in 2002.

control, the exit speed of the maneuver with an entrance speed of 43.4 mph and enabled stability control was greater than for the one begun at 43.5 mph with disabled stability control.

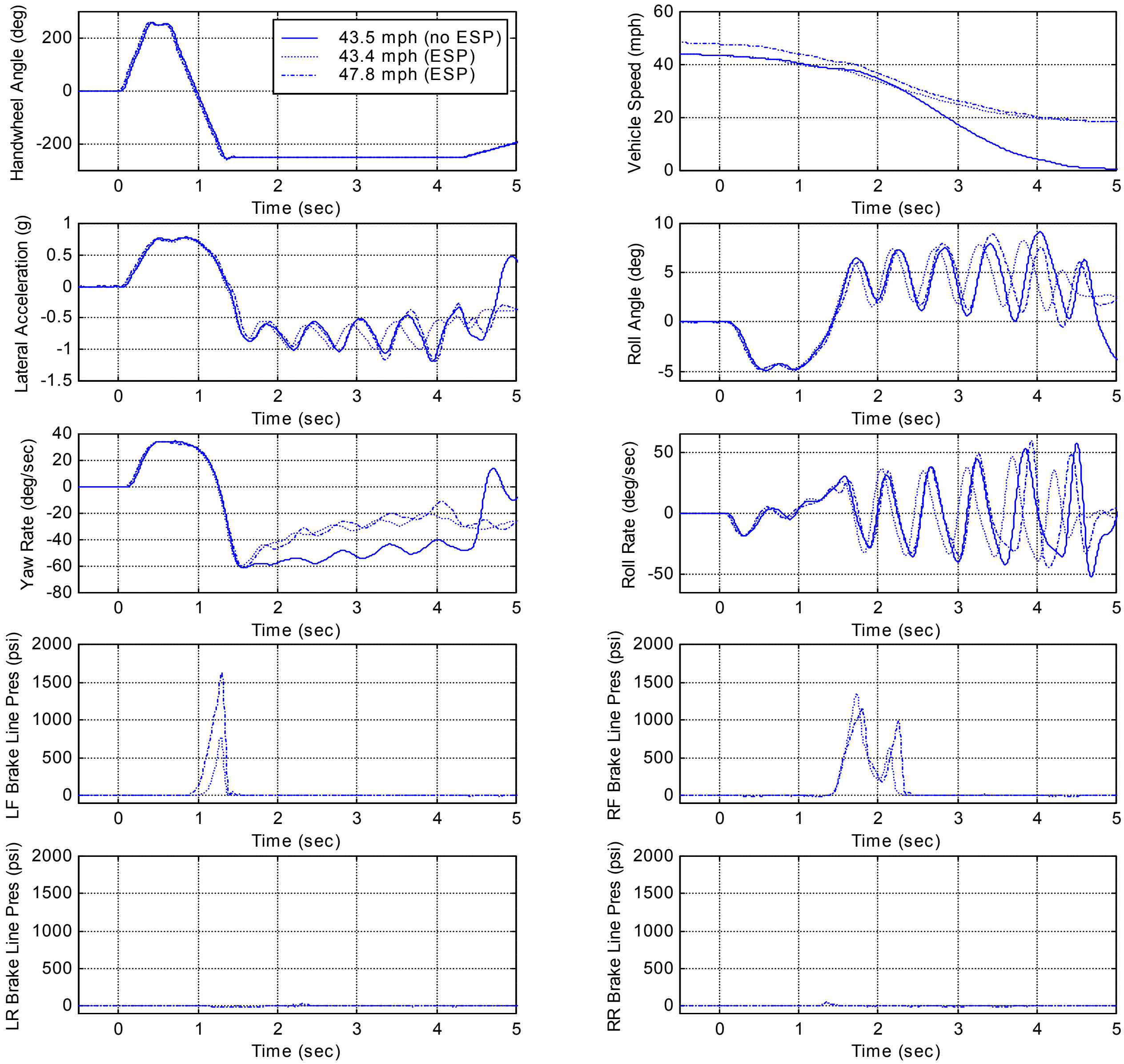

Figure 8.8. Fishhook 1a inputs and outputs for Mercedes ML320 tests performed with enabled and disabled stability control. Two-wheel lift occurred during the fifth roll oscillation during the test begun at 43.5 mph with disabled stability control, and during the fourth oscillation during the test begun at 47.8 mph with enabled stability control.

When an entrance speed of 47.8 mph was used during enabled stability control testing, the responses of the ML320 were similar to those observed during the disabled stability control test initiated at 43.5 mph. In this case, braking first occurred 0.9 seconds after the initial steering input (0.42 seconds after the reversal began), and lasted approximately 0.50 seconds. When compared to the test performed at 43.5 mph with disabled stability control, the effects of this intervention were not apparent. The second intervention occurred 1.4 seconds after the initial steer was input (0.81 seconds after the reversal was initiated). In this case, intervention was unable to effectively dampen the roll motion of the vehicle. Local lateral acceleration and roll angle peaks increased with each oscillation until two-wheel lift was produced. When compared to the test performed at 43.5 mph with disabled stability control, roll oscillations were of similar magnitude and frequency for a majority of the maneuver.

In agreement with the test performed at 43.4 mph, the most pronounced effect of stability control intervention during the test performed at 47.8 mph was in correcting the yaw rate of the vehicle after the steering reversal was input. The reduction of excessive yaw rate again affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were utilized, the exit speed of the maneuver begun at 47.8 mph with enabled stability control was greater than the one begun at 43.5 mph with disabled stability control. Interestingly, the exit speeds of the two tests shown in Figure 8.8 with enabled stability control were nearly equal.

8.6.3.2 Toyota 4Runner

Figure 8.9 presents three left-right Fishhook 1a maneuvers performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration. The figure includes a test performed at 40.2 mph with disabled stability control, the lowest speed for which two-wheel lift occurred in this configuration with the 4Runner. The tests performed with enabled stability control had maneuver entrance speeds of 43.1 and 47.6 mph. The 47.6 mph entrance speed was the lowest for which two-wheel lift occurred with the 4Runner in this configuration. The 43.1 mph test did not produce two-wheel lift. It is shown only to demonstrate how stability control affected vehicle response by presenting a test performed with an entrance speed similar to that producing two-wheel lift with disabled stability control.

For the tests shown in Figure 8.9, stability control intervention was detected during both tests for which it was enabled. In each case, brake torque was applied first to the right front and rear, then to the left front and rear of the vehicle in an attempt to correct what the stability control system interpreted as excessive oversteer conditions induced by the initial steer and countersteer inputs, respectively.

For the test performed at 43.1 mph, braking of the right front wheel first occurred 0.31 seconds after the steering input began (0.31 seconds *before* the reversal was initiated), and lasted approximately 1.16 seconds. This action was almost immediately supplemented with light right rear wheel braking that occurred 0.46 seconds after steering was first initiated (0.16 seconds *before* the reversal began), and lasted for the duration of the maneuver. When compared to the test performed at 40.2 mph with disabled stability control, the data presented in Figure 8.9 demonstrate that this intervention reduced the yaw rate established by the initial steer.

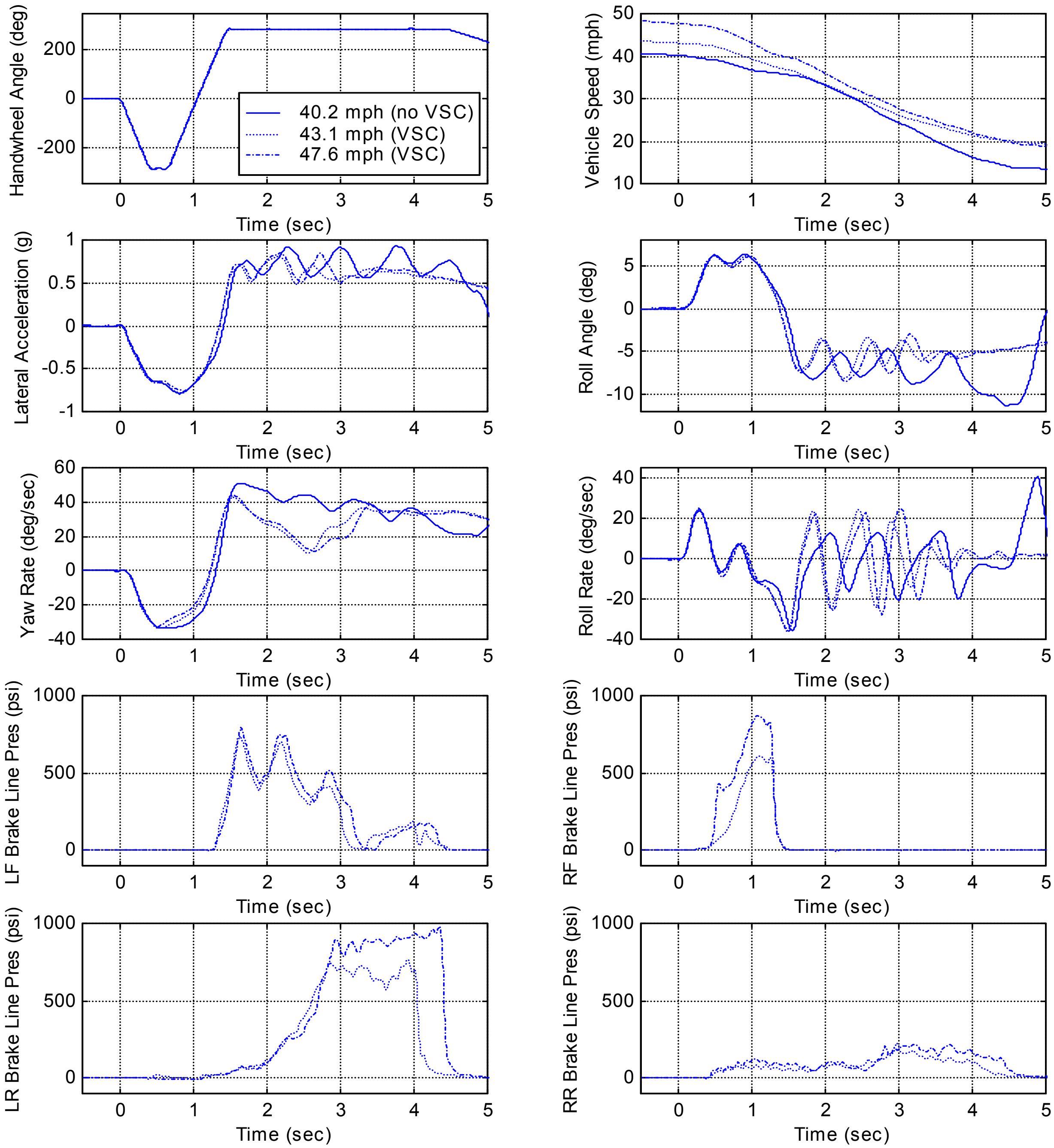

Figure 8.9. Fishhook 1a inputs and outputs for Toyota 4Runner tests performed with enabled and disabled stability control. Two-wheel lift occurred during the first through fourth roll oscillations during the test begun at 43.5 mph with disabled stability control, and during the second oscillation during the test begun at 47.8 mph with enabled stability control.

The second intervention during the test performed at 43.1 mph began with braking of the left rear wheel 1.13 seconds after the initial steer was input (0.51 seconds after the reversal was initiated). This action was almost immediately supplemented with left front wheel braking that occurred 1.31 seconds after steering was first initiated (0.69 seconds before the reversal began). Both braking events of the second intervention lasted for the duration of the maneuver, and resulted in some dampening of the roll motion of the vehicle. With the exception of the second peak roll angle oscillation value, the lateral acceleration, roll angle, and roll rate peak values were less than those for the test performed at 40.2 mph with disabled stability control.

In agreement with the Mercedes ML320 results, the most pronounced effect of the intervention that occurred during the test performed at 43.1 mph was how it affected the yaw rate of the vehicle after the steering reversal was input. The reduction of excessive yaw rate directly affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were made by the stability control, the exit speed of the maneuver begun at 43.1 mph with enabled stability control was greater than begun the one at 40.2 mph with disabled stability control. Unlike the ML320 results shown in Figure 8.8, stability control intervention reduced the post-reversal peak yaw rate magnitude. The peak yaw rate of the 4Runner test performed at 43.1 mph with enabled stability control was 18.3 percent less than that produced during the 40.2 mph test with disabled stability control.

When an entrance speed of 47.6 mph was used during enabled stability control tests, the responses of the 4Runner were more similar to those produced during the enabled stability control test initiated at 43.1 mph than to those produced at 40.2 mph with disabled stability control. In this case, right front braking first occurred 0.30 seconds after the initial steer input began (0.32 seconds *before* the reversal was initiated), and lasted approximately 1.19 seconds. This action was almost immediately supplemented with light right rear wheel braking that occurred 0.43 seconds after steering was first initiated (0.19 seconds *before* the reversal began), and lasted for the duration of the maneuver. This intervention reduced the yaw rate established by the initial steer more than either of the other tests shown in Figure 8.9.

The second intervention of the test performed at 47.6 mph began with braking of the left rear wheel 1.15 seconds after the initial steer was input (0.53 seconds after the reversal was initiated). This action was almost immediately supplemented with left front wheel braking that occurred 1.29 seconds after steering was first initiated (0.67 seconds before the reversal began). In this case, intervention was unable to effectively dampen the roll motion of the vehicle, and two-wheel lift was produced during the second roll oscillation. Local lateral acceleration and roll angle peaks increased with each oscillation until two-wheel lift was produced. When compared to the test performed at 40.2 mph with disabled stability control, roll oscillations were generally of lesser magnitude for a majority of the maneuver.

In agreement with the enabled stability control test performed at 43.1 mph, the most pronounced effect of stability control intervention during the test performed at 47.6 mph was in correcting the yaw rate of the vehicle after the steering reversal was input. The suppression of excessive yaw rate continued to affect the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were utilized, the exit speed of maneuver begun at 47.6 mph with enabled stability control remained greater than the one begun at 40.2 mph with disabled stability control. In agreement with the previously discussed ML320 comparison, the exit speeds of the two tests shown in Figure 8.9 with enabled stability control were nearly equal.

8.7 Fishhook 1a Maneuver Assessment

Using the evaluation factors presented in Chapter 2, the authors have rated the Fishhook 1a maneuver in the following manner:

Objectivity and Repeatability = Excellent

Fishhook 1a was performed with excellent objectivity and repeatability. By using the programmable steering machine, handwheel inputs were precisely executed, and able to be replicated from run-to-run. Test drivers were able to achieve maneuver entrance speeds an average of ± 1.4 mph from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data during Fishhook 1a tests were highly repeatable. That said, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, poorer than at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of Fishhook 1a maneuver.

Performability = Good

Objective and repeatable Fishhook 1a maneuvers were easily performed with the programmable steering controller. The test procedure was well developed, and adapted handwheel input *magnitudes* to the vehicle being evaluated. That said, the *timing* of these inputs (the duration of the dwell time) did not change from vehicle-to-vehicle. Although this did not impede the ability of Fishhook 1a to induce two-wheel lift during Phase IV, the sample population was very small. If a larger population were to be considered, the authors expect the fixed dwell time will result in some vehicles not being tested with the timing needed to achieve worst case rollover performance.

Discriminatory Capability = Excellent

Fishhook 1a was an excellent maneuver for measuring the rollover resistance of different vehicles. Two-wheel lift was produced during tests performed with the Chevrolet Blazer and Mercedes ML320 (with enabled and disabled stability control) in the Nominal Load configuration. Each Phase IV vehicle tested in the Reduced Rollover Resistance configuration experienced two-wheel lift, regardless of whether its stability control was enabled or disabled (if so equipped).

Although the Mercedes ML320 was not evaluated in the Reduced Rollover Resistance configuration, the authors are certain it would have been exhibited two-wheel lift during tests performed in the this configuration. Reduced Rollover Resistance configuration raises a vehicle's center of gravity height. This action will encourage, not prevent, two-wheel lift.

While Fishhook 1a does an excellent job of discriminating between different levels of untripped rollover resistance for typical, current generation, sport utility vehicles, it is unlikely the maneuver will be capable of such discrimination for the entire light vehicle fleet. The authors do not anticipate many two-wheel lifts will occur during testing of vehicles that have a Static Stability Factors of 1.13 or greater (e.g., vehicles that earn three or more stars under NHTSA's current rollover rating program). That said, Fishhook 1a is one of only two maneuvers known to NHTSA to cause two-wheel lifts for vehicles in the above 1.13 SSF range (e.g., for the Mercedes ML320). Therefore, the Fishhook 1a maneuver does as good a job of discriminating throughout the entire fleet of vehicles as will any other on-road, untripped Rollover Resistance maneuver if the occurrence of two-wheel lift is used as a criterion.

Appearance of Reality = Excellent

The handwheel inputs defining any fishhook maneuver approximate the steering a startled driver might use in an effort to regain lane position on a two-lane road after dropping two wheels off onto the shoulder. None of the Fishhooks simulate the effects of the actual road-edge drop-off.

9.0 NHTSA FISHHOOK 1B

Fishhook 1b (also called the Roll Rate Feedback Fishhook) was one of four closed-loop Rollover Resistance maneuvers used in Phase IV[1]. Unlike the other three closed loop maneuvers, the control loop for Fishhook 1b was closed by the steering machine instead of by the driver.

The Fishhook 1b maneuver was derived from the Fishhook 1 maneuver used during Phase II. Its steering magnitudes and rates were identical to those of Fishhook 1a; however, the duration of its dwell time (the time between completion of the initial steering ramp and the initiation of the countersteer) was not fixed. Fishhook 1b was a closed-loop maneuver whose dwell times were defined by the roll motion of the vehicle being evaluated. Fishhook 1b used automated steering inputs commanded by the programmable steering machine.

This chapter is comprised of seven sections. Section 9.1 describes the maneuver and how it was executed. Section 9.2 and 9.3 discuss the steering and vehicle speed input repeatability, respectively. Section 9.4 discusses maneuver entrance speed variability. Section 9.5 discusses output repeatability. Section 9.6 presents test results. Section 9.7 provides a maneuver assessment and concluding remarks.

9.1 Fishhook 1b Maneuver Description

To begin this maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, initiated the handwheel commands described in Figure 9.1. Following completion of the countersteer, handwheel position was maintained for three seconds. The handwheel was then returned to zero.

As was the case for Fishhook 1a, the Fishhook 1b handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the Slowly Increasing Steer maneuver (at 50 mph) by a scalar of 6.5. The handwheel rates of the initial steer and countersteer ramps were 720 degrees per second. Table 9.1 presents the Fishhook 1a handwheel inputs used in Phase IV.

Unlike Fishhook 1a, dwell times for Fishhook 1b varied from test-to-test. They were determined by having the steering machine monitor roll rate (roll velocity). If an initial steer to the left was input, the steering reversal following completion of the first handwheel ramp occurred when the roll rate of the vehicle first equaled or went below 1.5 degrees per second. If an initial steer to the right was input, the steering reversal following completion of the first handwheel ramp occurred when the roll rate of the vehicle first equaled or exceeded -1.5 degrees per second.

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[1] These maneuvers include the Fishhook 1b, the Path Corrected Limit Lane Change, the ISO 3888 Part 2 Double Lane Change, and the Consumers Union Short Course Double Lane Change.

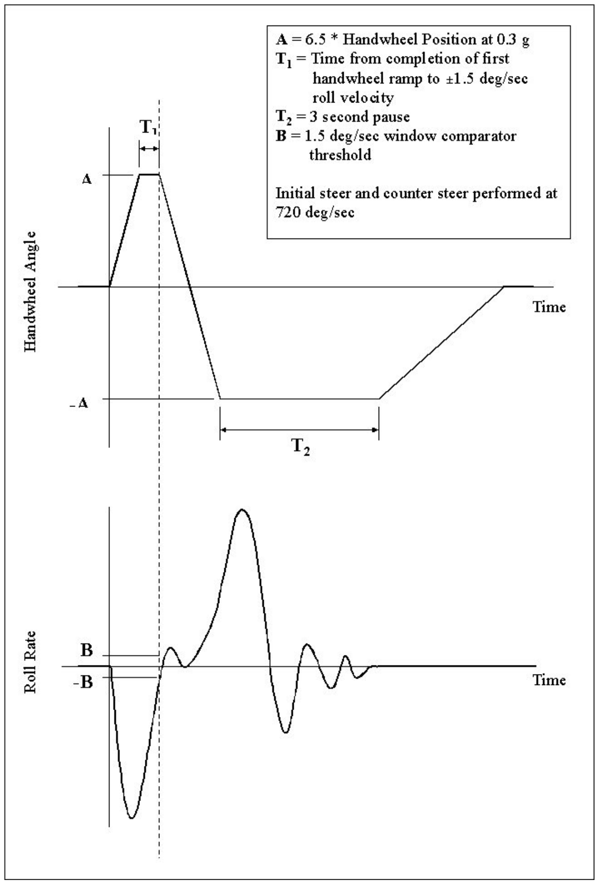

Figure 9.1. Fishhook 1b maneuver description.

Table 9.1. Phase IV Fishhook 1b Maneuver Handwheel Input Magnitudes.

Vehicle	Phase IV Fishhook 1b Handwheel Inputs[1] (degrees)		
	Nominal	**Reduced Rollover Resistance**	**Modified Handling**
Chevrolet Blazer	326	326	280
Toyota 4Runner (enabled and disabled stability control)	287	287	257
Mercedes ML320 (enabled and disabled stability control)	252	Not Tested	278
Ford Escape	233	233	217

[1]All Phase IV Fishhook 1b maneuvers used handwheel rates of 720 degrees per second.

9.2 Fishhook 1b Steering Input Repeatability

The handwheel magnitudes used to define Fishhook 1b were vehicle dependent, based on lateral acceleration data produced during Slowly Increasing Steer tests. Unlike Fishhook 1a, however, the dwell time between the completion of the first handwheel ramp and the beginning of the steering reversal was a function of each vehicle's roll response. For this reason, the assessment of steering repeatability was more involved than that of Fishhook 1a.

Fishhook 1b steering repeatability analyses were broken down into two components. First, handwheel magnitude repeatability was evaluated. Because maneuver entrance speed was used as a severity metric for Fishhook 1b, a number of speed iterations were needed before a termination condition was realized. The handwheel input magnitudes remained constant throughout this iterative process, thus providing an opportunity for repeatability assessment. Figure 9.2 presents these data for the Mercedes ML320. All four right-left steer tests performed in the Nominal Load configuration with stability control are represented. The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the initial handwheel ramps and final steering holds of individual tests from each other. The width of the countersteer ramp was due to run-to-run variations in dwell time. The ripples immediately after the first handwheel ramp, as well as immediately before and after the second handwheel ramp, were due to a combination of factors, including the filter applied to the data during post-processing and a slight steering machine input overshoot.

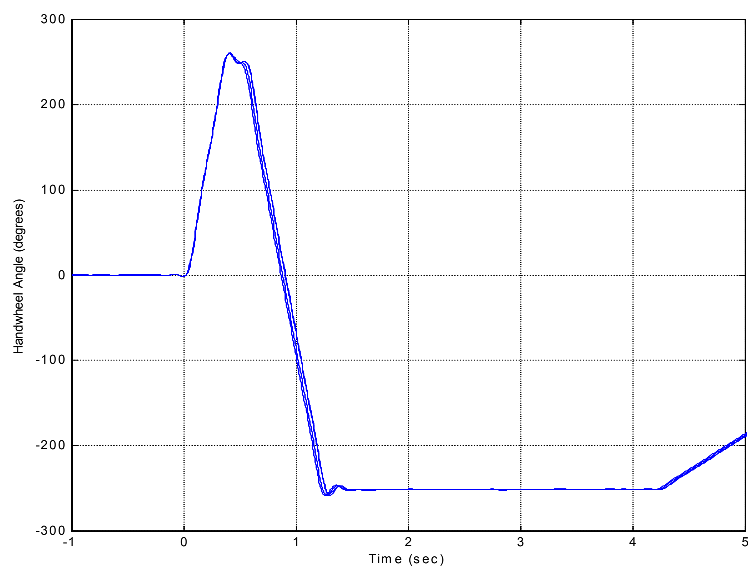

Figure 9.2. Handwheel inputs recorded during four Mercedes ML320 Fishhook 1b maneuvers.

Dwell time repeatability was the second Fishhook 1b component evaluated in Phase IV. Because the dwell time was dependent on a vehicle's roll response following completion of the first handwheel ramp, simply comparing duration was not appropriate. Reversing handwheel direction of steer at maximum roll angle was a closed-loop procedure, adaptable to test variations (e.g., maneuver entrance speed, loading, etc.). Consequentially, some differences in dwell time duration within a particular test sequence were expected. Therefore, assessment of dwell time repeatability was really a measure of how well the method worked, i.e., did handwheel reversals occur when expected.

The steering machine was equipped with the ability to output a signal acknowledging when roll rate was within the comparison window, the "Roll Flag." Just prior to the steering input, the vehicle was driven in a straight line. Because no significant changes in chassis roll angle were occurring, the roll rate was nearly zero and therefore within the "1.5 degrees per second comparison window. This caused the Roll Flag signal to be set too high. Upon input of the first handwheel ramp, the vehicle began to roll. As roll rate increased beyond the window comparator threshold, the Roll Flag was set to low. After completion of the first handwheel ramp, the vehicle eventually reached its maximum roll angle. As this was achieved, the roll rate entered the comparison window, setting the Roll Flag again to high. The methodology check used to assess dwell time repeatability compared the roll rate of the vehicle at this instant to the nominal "1.5 degrees per second window comparator thresholds.

A total of 162 valid Fishhook 1b tests were performed in Phase IV. For every test, the Roll Flag was set high within two data counts (10 ms) of the roll rate first passing through the window comparator threshold ("1.5 degrees per second) after the initial steer. In 136 of these tests (84 percent), the Roll Flag was set high within one data count (5 ms) of the roll rate first passing through the window comparator threshold

Figure 9.3 presents handwheel angle, roll angle, roll rate, and Roll Flag data for two of the four tests shown in Figure 9.2. To highlight the area of greatest interest (completion of the first handwheel ramp, occurrence of maximum roll angle, and initiation of the steering reversal), only data from time zero to 1.5 seconds are provided.

Once the steering machine recognized the roll rate zero crossing, the direction of steer was reversed. Table 9.2 summarizes the average response delays from the time the Roll Flag was set high to when the handwheel reversal was actually observed. These lags were generally small, with average values (calculated from all tests run for each vehicle and configuration) ranging from 10 to 24 milliseconds.

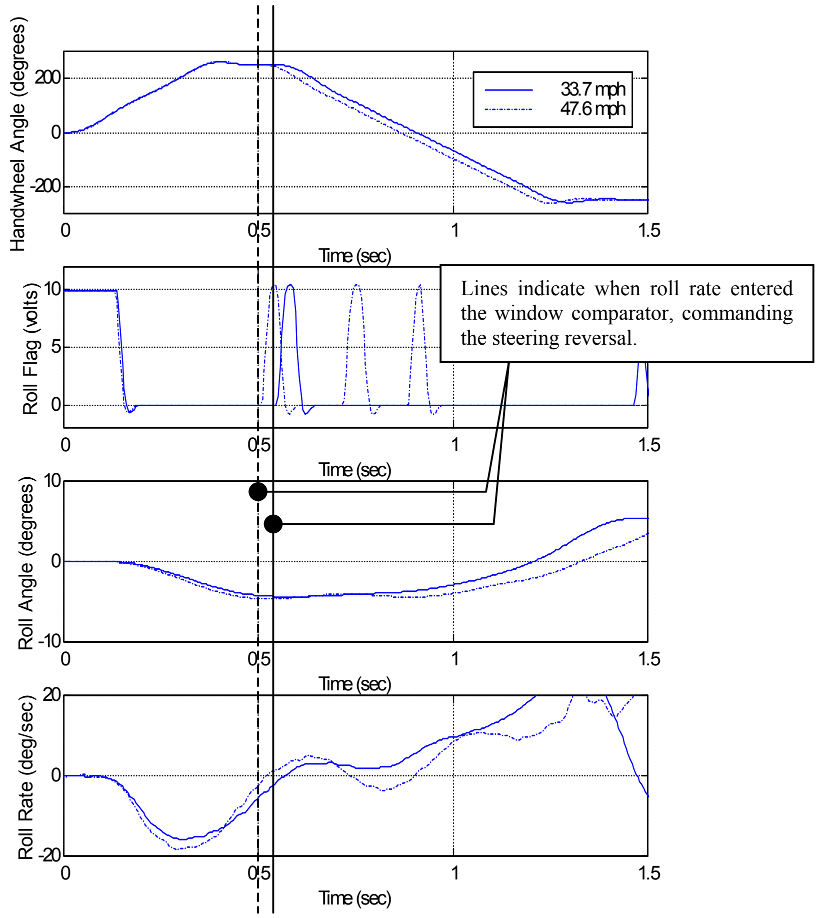

Figure 9.3. Handwheel angle, Roll Flag, roll angle, and roll rate data recorded during two Mercedes ML320 Fishhook 1b maneuvers performed at different speeds. Roll Flag has rounded transitions and overshoot due to filtering of the data.

Table 9.2. Fishhook 1b Reversal Lag Time Summary.

Vehicle	Nominal Load		Reduced Rollover Resistance		Modified Handling	
	Average (ms)	Std Dev (ms)	Average (ms)	Std Dev (ms)	Average (ms)	Std Dev (ms)
Blazer	22	9	11	8	10	5
4Runner (VSC)	19	6	14	5	11	6
4Runner (disabled VSC)	12	5	13	3	10	4
ML320 (ESP)	24	8	N/A (Tests not performed)		14	6
ML320 (disabled ESP)	19	5			14	7
Ford Escape	20	4	22	5	19	2

9.3 Fishhook 1b Vehicle Speed Repeatability

Figure 9.4 presents handwheel position, vehicle speed, and VSC intervention data for four Fishhook 1b tests performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration. The data were collected during tests performed at 39.9, 40.3, and 39.5 mph without stability control. For this configuration, only one comparable test was performed with stability control, at 40.1 mph (recall the tests performed with enabled and disabled stability control were contained in two unique test series). As seen in the figure, stability control intervention occurred 15 ms after completion of the first handwheel ramp. Unlike the J-Turn, the manner in which vehicle speed decreased with and without stability control differed noticeably. After completion of the first handwheel ramp, vehicle speed first slowed at a greater rate with enabled stability control due to brake application. Then it slowed less rapidly as the reduction in yaw rate caused by the stability control's intervention caused less speed to be scrubbed-off. Starting approximately 2.6 seconds after time zero, despite the braking, the vehicle speed with stability control became *greater* than that without it.

When the handwheel was returned back to zero degrees following completion of the maneuver (not pictured in Figure 9.4), the vehicle speed with stability control was 19.4 mph, 52 percent lower than the 40.1 mph entrance speed. When stability control had been disabled, the average vehicle speed for the three runs was 13.3 mph, 67 percent lower than the 39.9 mph average entrance speed.

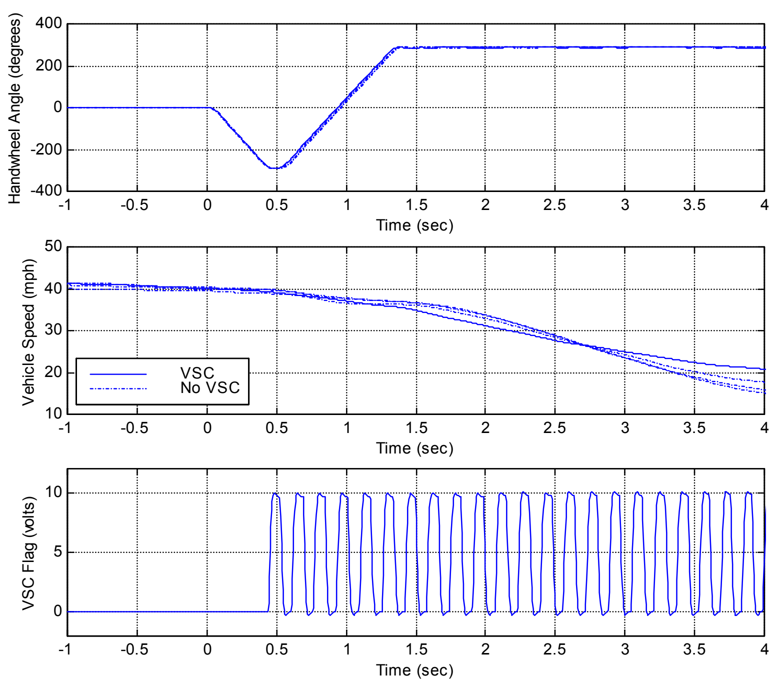

Figure 9.4. Handwheel angle, vehicle speed, and stability control intervention data recorded during four Toyota 4Runner Fishhook 1b tests. The VSC Flag signal cycles during stability control intervention and is rounded due to filtering of the data.

9.4 Fishhook 1b Entrance Speed Variability

When all valid Fishhook 1b tests were considered, for each vehicle in all configurations, the driver was able to achieve entrance speeds within ±4.1mph (8.7 percent) of the desired target speed. The actual and target maneuver entrance speed differed by an average of ±1.3 mph (3.1 percent) overall. Fishhook 1b entrance speed variability was in agreement with that of other maneuvers performed with the steering machine.

9.5 Fishhook 1b Output Repeatability

The severity metric used for all fishhook maneuvers was maneuver entrance speed. Since, in general, multiple tests were not run at the same maneuver entrance speed, and because handwheel dwell times differed from test-to-test, data available for the assessment of test output repeatability was limited. If a test produced at least two inches of simultaneous two-wheel lift during a particular test series, entrance speed was iteratively decreased in approximately 1 mph increments. In some cases, the downward iteration resulted in entrance speeds nearly equal to those used in the upward iterations prior to the occurrence of two-wheel lift.

Figure 9.5 presents test output data for three Fishhook 1b tests performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration with disabled stability control. The entrance speeds of Test 865, 867, and 869 were 39.9, 40.3, and 39.5 mph, respectively. Due to the comparable speeds and dwell times of these tests, output repeatability could be reasonably assessed. The dwell times of these tests ranged from 110 to 120 ms.

Figure 9.5 demonstrates the excellent output repeatability found before the steering reversals; it was impossible to distinguish the individual tests from each other. Post reversal repeatability was also good for tests producing similar two-wheel lift magnitudes.

Table 9.3 summarizes the seven left-right Fishhook 1b tests performed with the Toyota 4Runner (disabled stability control) in the Reduced Rollover Resistance configuration.

Test 865 was the third in a series of seven left-right Fishhook 1b tests performed with the Toyota 4Runner. Although the nominal entrance speed of Test 865 should have been 45 mph (being the third test in the series), the driver was uncomfortable with the 5 mph entrance speed increase from the second test. Therefore, a nominal entrance speed increase of 2 mph, to 42 mph, was used. Speed input variability resulted in an actual entrance speed of 39.9 mph. This test produced approximately one inch of simultaneous two-wheel lift. Because this was less than the two inch termination requirement, testing proceeded to the next severity level. The nominal entrance speed was increased by another 2 mph, to 44 mph. The fourth test, performed at 42.3 mph, produced enough two-wheel lift to contact the front and rear outriggers. As a result, entrance speed was iteratively decreased.

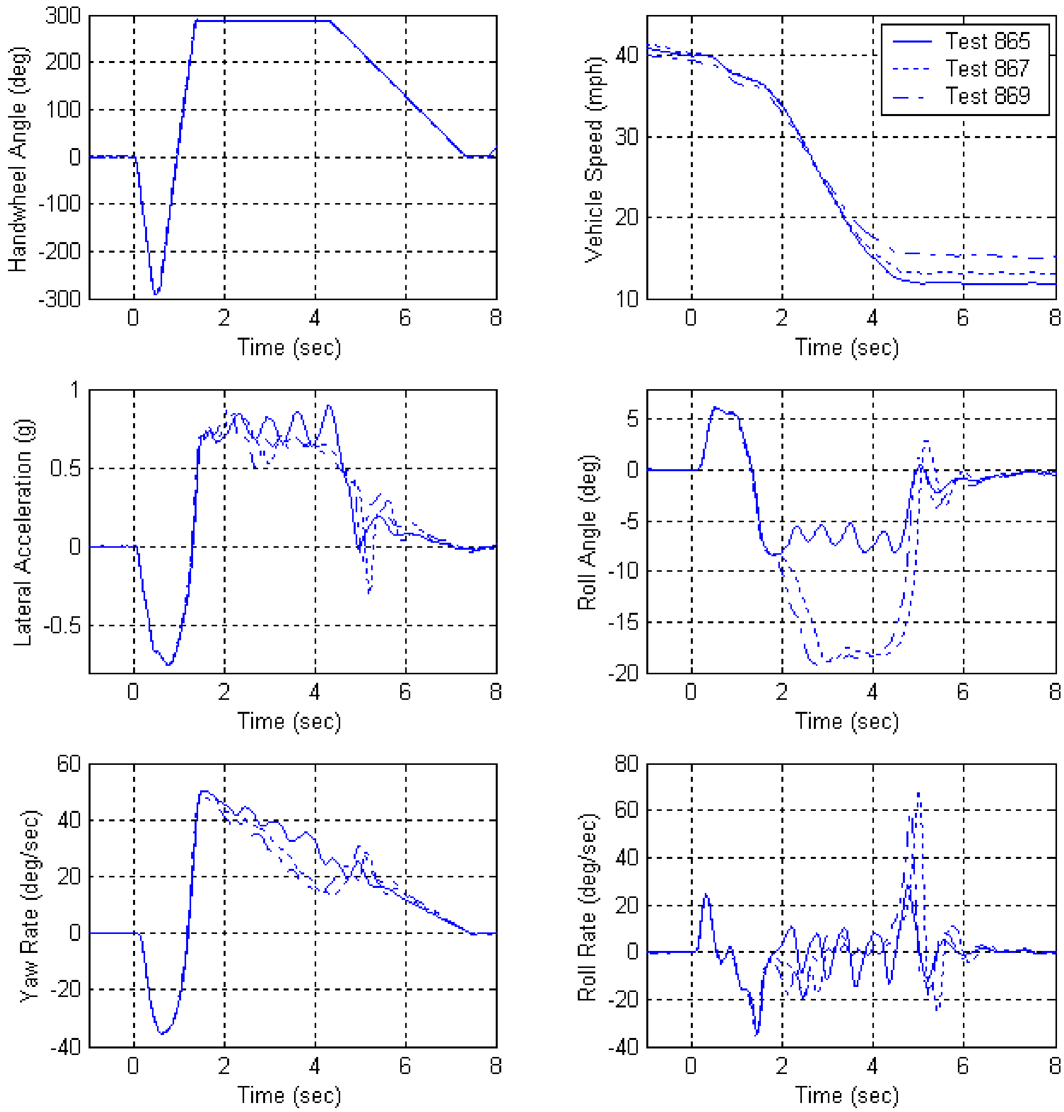

Figure 9.5. Inputs and outputs recorded during four Toyota 4Runner Fishhook 1b tests performed with disabled stability control.

At test driver request, a downward speed increment of 2 mph was used, rather than the normal one mph. Test 867 was the fifth test in the series, and was performed at a nominal entrance speed of 42 mph and an actual entrance speed of 40.3 mph. As with the preceding test, enough two-wheel lift to contact the front and rear outriggers was produced. The sixth test, performed at a nominal 40 mph and an actual entrance speed of 38.4 mph, produced approximately one inch of simultaneous two-wheel lift.

Because this was less than the two inch termination requirement, the nominal entrance speed was increased one mph for the seventh (and final) test, so as to better isolate the minimum entrance speed for which at least two inches of two-wheel could be detected. Test 869 was performed at 39.5 mph, and produced enough two-wheel lift to contact the front and rear outriggers.

Table 9.3. Output Summary for Left-Right Fishhook 1b Tests Performed With the Toyota 4Runner in the Reduced Rollover Resistance Configuration (Disabled Stability Control).

Test Number	Entrance Speed (mph)		Dwell Time (ms)	Two-Wheel Lift (inches)	Maximum Lateral Acceleration (g)		Maximum Roll Angle (deg)		Maximum Roll Rate (deg/sec)		Maximum Yaw Rate (deg/sec)	
	Nominal	Actual			Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal	Pre-Reversal	Post-Reversal
863	35	35.5	120	None	0.72	0.86	6.2	7.7	22.8	33.2	36.0	41.0
864	40	38.3	125	1	0.74	0.90	6.3	8.5	23.8	34.4	35.7	46.6
865	**42**	**39.9**	**120**	**1**	**0.75**	**0.91**	**6.2**	**8.4**	**23.9**	**34.7**	**35.2**	**50.2**
866	44	42.3	140	18[1]	0.77	0.93	6.4	19.2	24.8	33.4	35.2	55.7
867	**42**	**40.3**	**115**	**18[1]**	**0.75**	**0.85**	**6.3**	**18.9**	**24.4**	**33.8**	**35.4**	**50.4**
868	40	38.4	120	2	0.74	0.82	6.3	8.0	24.1	34.5	35.6	46.3
869	**41**	**39.5**	**110**	**18[1]**	**0.74**	**0.83**	**6.3**	**19.5**	**24.1**	**35.2**	**35.3**	**48.2**

Note: Highlighted tests were included in Figure 9.5.

[1]Additional two-wheel lift was suppressed by front and rear outrigger contact with the ground.

Due to the relatively small number of left-right Fishhook 1b tests performed in the Reduced Rollover Resistance this test sequence, the authors think it unlikely that tire wear was the primary cause for the differences in two-wheel lift severity between Tests 865, 867, and 869. A better explanation is that at approximately 40 mph, in this loading configuration, the 4Runner was operating at a threshold for which two-wheel lift of two inches or more was possible. In agreement with the Fishhook 1a test results discussed in the previous section, different roll responses were possible from equivalent inputs.

9.6 Fishhook 1b Results

9.6.1 Two-Wheel Lift

The Fishhook 1b maneuver was an effective closed-loop maneuver for assessing the dynamic rollover propensity of the Phase IV test vehicles. Conduct of the Fishhook 1b maneuver produced numerous two-wheel lifts. Table 9.4 summarizes the occurrence of these wheel lifts for Fishhook 1b tests performed in the Nominal Load, Reduced Rollover Resistance, and Modified Handling test configurations. Note that the Mercedes ML320 was not tested in the Reduced Rollover Resistance configuration due to the severity of its roll oscillations during testing in the Nominal Load configuration.

9.6.1.1 Nominal Load

Five situations resulting in two-wheel lift occurred during Phase IV Fishhook 1b testing performed in the Nominal Load configuration: two with the Chevrolet Blazer and three with the Mercedes ML320.

The speeds at which two-wheel lift occurred with the Chevrolet Blazer were in good agreement. The lowest maneuver entrance speed for which two-wheel lift was produced during a left-right test was 40.3 mph. Right-left steering produced two-wheel lift when a maneuver entrance speed of 40.1 was used.

The ML320 exhibited a greater rollover propensity during tests performed with disabled stability control (compared to those performed with it enabled). When left-right handwheel inputs were used, stability control increased maneuver entrance speed to 49.9 mph before two-wheel lift occurred. With stability control disabled, left-right steering produced two-wheel lift during a test performed at 46.4 mph. No two-wheel lift occurred when right-left steering was input with enabled stability control in the Nominal Load configuration. When disabled, two-wheel lift occurred during a test performed at 50.6 mph, slightly above the maximum nominal maneuver entrance speed of 50 mph.

9.6.1.2 Reduced Rollover Resistance

The Reduced Rollover Resistance configuration increased each vehicle's dynamic rollover propensity. The extent of its influence varied from vehicle to vehicle.

The Toyota 4Runner with disabled stability control was the vehicle most affected by changing to the Reduced Rollover Resistance configuration. With enabled stability control, the 4Runner was the least affected vehicle. In this configuration, the 4Runner exhibited a greater rollover propensity during tests performed with disabled stability control (compared to those with it enabled). Left-right steering inputs did not produce two-wheel lift when stability control was enabled. With stability control disabled, left-right steering produced two-wheel lift during a test performed at 39.5 mph. With right-left steering and enabled stability control, two inches (or more) of two-wheel lift first occurred at a maneuver entrance speed of 49.6 mph. This entrance speed was only slightly below the nominal termination speed of 50 mph; the right-left steering performance of this vehicle may not actually have been substantially worse than its left-right steering performance. With stability control disabled, two-wheel lift occurred during a test performed at 37.7 mph.

Consistent with the Nominal Load configuration, the Chevrolet Blazer produced two-wheel lift for both left-right and right-left steering in the Reduced Rollover Resistance configuration. The maneuver entrance speeds at which the two-wheel lift occurred remained in good agreement. Two-wheel lift was produced during a left-right test at 36.8 mph with the Blazer. Right-left steering produced two-wheel lift at an entrance speed of 36.2 mph.

Two-wheel lift was produced at 46.0 mph with the Ford Escape in the Reduced Rollover configuration with left-right steering. No two-wheel lift was produced when right-left steering was used.

The Mercedes ML-320 was not tested in the Reduced Rollover Resistance configuration due to the severity of its roll oscillations during testing in the Nominal Load configuration. Since this vehicle had two-wheel lift in the Nominal Load configuration for right left steering with stability control enabled and for both left-right and right-left steering with stability control disabled, the authors believe that two-wheel lift would have occurred for all situations if this vehicle had been tested in the Reduced Rollover configuration.

9.6.1.3 Modified Handling

Five situations resulting in two-wheel lift occurred during Fishhook 1b tests performed with the Modified Handling configuration: two with the Chevrolet Blazer and three with the Mercedes ML320.

Consistent with Nominal Load and Reduced Rollover Resistance configuration results, the Chevrolet Blazer produced two-wheel lift for both left-right and right-left steering in the Modified Handling configuration. Two-wheel lift was produced during a left-right test performed at 34.9 mph (the lowest speed for which two-wheel lift occurred during the Phase IV testing, regardless of vehicle or configuration). Right-left steering produced two-wheel lift when a maneuver entrance speed of 46.9 mph was used. Unlike those that occurred with the other Fishhook 1b loading configurations with the Blazer, the speeds at which the two-wheel lift occurred for the steering combinations differed by 12.0 mph.

This large differential between the entrance speeds resulting in two-wheel lift with left-right and right-left steering for the Chevrolet Blazer may have been due to the manner in which the test series was performed. When right-left steering was input, vehicle speed was iteratively increased to a nominal 50 mph (the actual maneuver entrance speed was 46.9 mph). Two-wheel lift occurred during this test. Rather than iteratively decrease vehicle speed in the usual 1 mph increments, one final test was performed with a nominal entrance speed of 47 mph. Regrettably, sensor outputs (e.g., vehicle speed) were not recorded during this test due to a data acquisition system malfunction. Video data was recorded, however, and showed that no two-wheel lift had occurred. Additional tests were not performed due to driver discomfort. The actual speed of the final test is unknown.

Fishhook 1b tests performed with the ML320 in the Modified Handling configuration found a nearly equivalent rollover propensity to that of the Nominal Load configuration. Two-wheel lift occurred during a test performed at 51.7 mph with left-right steering and enabled stability control. No two-wheel lift was produced with right-left steering with enabled stability control. When stability control was disabled, a maneuver entrance speed of 51.3 mph produced two-wheel lift. Right-left steering produced two-wheel lift during a test performed at 51.9 mph, again with disabled stability control. The maneuver entrance speed of all tests for which two-wheel lift was occurred with the ML320 in the Modified Handling configuration occurred were above the nominal maximum entrance speed of 50 mph.

Neither the Toyota 4Runner nor the Ford Escape had two-wheel lift when tested in the Modified Handling configuration.

Table 9.4. Fishhook 1b Two-Wheel Lift Summary.

Vehicle	Stability Control Status	Configuration					
		Nominal Load		Reduced Rollover Resistance		Modified Handling	
		Left-Right Steer (mph)	Right-Left Steer (mph)	Left-Right Steer (mph)	Right-Left Steer (mph)	Left-Right Steer (mph)	Right-Left Steer (mph)
2001 Toyota 4Runner	Enabled	None (Max Speed = 48.7)	None (Max Speed = 50.1)	None (Max Speed = 49.7)	49.6	None (Max Speed = 51.1)	None (Max Speed = 50.8)
	Disabled	None (Max Speed = 48.0)	None (Max Speed = 48.4)	39.5	37.7	None (Max Speed = 50.5)	None (Max Speed = 50.0)
2001 Chevrolet Blazer	N/A	40.3	40.1	36.8	36.2	34.9[1]	46.9[1]
2001 Ford Escape	N/A	None (Max Speed = 51.6)	None (Max Speed = 50.8)	46.0	None (Max Speed = 50.2)	None (Max Speed = 49.1)	None (Max Speed = 49.0)
1999 Mercedes ML320	Enabled	49.9	None (Max Speed = 47.6)	Tests not performed		51.7	None (Max Speed = 51.5)
	Disabled	46.4	50.6			51.3	51.9

[1]The lowest maneuver entrance speed resulting in two-wheel lift with left-right steering differed significantly from that resulting from right-left steering for the Chevrolet Blazer in the Modified Handling configuration. Since the right-left sequence was prematurely terminated (due to driver discomfort), it is unlikely the lowest entrance speed capable of producing two-wheel lift with right-left steering was isolated.

9.6.2 Tire Debeading and Rim Contact

Four occurrences of debeading and/or rim-to-pavement contact happened during Fishhook 1b tests. All were produced by the Mercedes ML320. Unlike during Fishhook 1a testing, debeading and/or rim contact occurred at the outside front and/or outside *rear* of the vehicle. Table 9.5 summarizes these occurrences. Debeading and/or rim-to-pavement contact occurred with stability control both enabled and disabled in the Nominal Load configuration, and with disabled stability control in the Modified Handling configuration. All maneuver entrance speed iterations were in accordance with that specified in the "Fishhook 1b Maneuver Description."

Table 9.5. Debeads and Rim-To-Pavement Contact During Fishhook 1b Testing

Vehicle	Configur-ation	Stability Control Status	Entrance Speed (mph)	Direction of Steer	Innertube Installation	Location of Debead	Location of Rim Contact	Number of Tests Prior to Debead or Rim Contact
Mercedes ML320	Nominal Load	Active	49.9	Left-Right	None	Left Front	Left Front (debead)	3
		Disabled	50.6	Right-Left	Left Front, Right Front	None	Right Front, Right Rear	3
		Disabled	50.8	Left-Right	Left Front, Right Front	Left Rear	Left Rear (debead)	3
	Modified Handling	Active	51.7	Left-Right	Left Front, Right Front	None	Left Front	3

In agreement with the vehicle responses produced during Fishhook 1a tests, the combination of high maneuver entrance speed and Fishhook 1b handwheel inputs set the Mercedes ML320 into repeated, apparently negatively damped, roll oscillations. As the amplitude of the roll motion increased, the lateral accelerations produced by the ML320 became much greater than for other Phase IV vehicles. For example, the maximum lateral acceleration during the test producing the left rear debead was 1.79 g. This was the largest lateral acceleration recorded in Phase IV.

To better understand why Fishhook maneuver severity was so high for the Mercedes ML320, the authors considered the forces acting on the outside front tire during conduct of these maneuvers. A six-component wheel load transducer assembly was installed at the left front corner of the vehicle, replacing the wheel (see Figure 9.6)[2].

[2] Additional tests performed with the ML320 (to research dynamic loading capable of producing rim-to-pavement contact) and a more detailed comparison with in-lab bead unseat tests will be presented in [19].

Figure 9.6. Six-component wheel load transducer installed on the Mercedes ML320.

Fishhook 1b tests were performed in the Nominal Load configuration, with left-right steering and disabled stability control. Nominal maneuver entrance speed began at 35 mph, and was iteratively increased to 45 mph in 5 mph increments. Innertubes were installed in each of the four tires for all tests.

Tests performed at 36.7 and 41.7 mph did not produce any rim-to-pavement contact. When tested at 47.3 mph, however, abrupt rim-to-pavement contact was made. Figure 9.7 presents wheel force data for the test. The lateral force produced at the third roll peak (one oscillation prior contact) was 5067 lbf. Once contact was made, lateral force increased substantially. Unfortunately, determining the extent of the increase for the fourth and fifth roll peaks was not possible, as transducer output clipped at 6027 lbf.

Tests performed with the six-component wheel load transducer quantified the lateral forces produced at the outside front corner of the ML320 during conduct of Fishhook 1b maneuvers with disabled stability control. When performed at speeds between 45 and 50 mph, these forces were very high. It remains unknown why the ML320 exhibited such extreme roll oscillations during fishhook testing. However, knowing that such high vertical forces were attainable by the vehicle explains why the ML320 could achieve the high response magnitudes (e.g., lateral acceleration and roll rate) presented several places in this report.

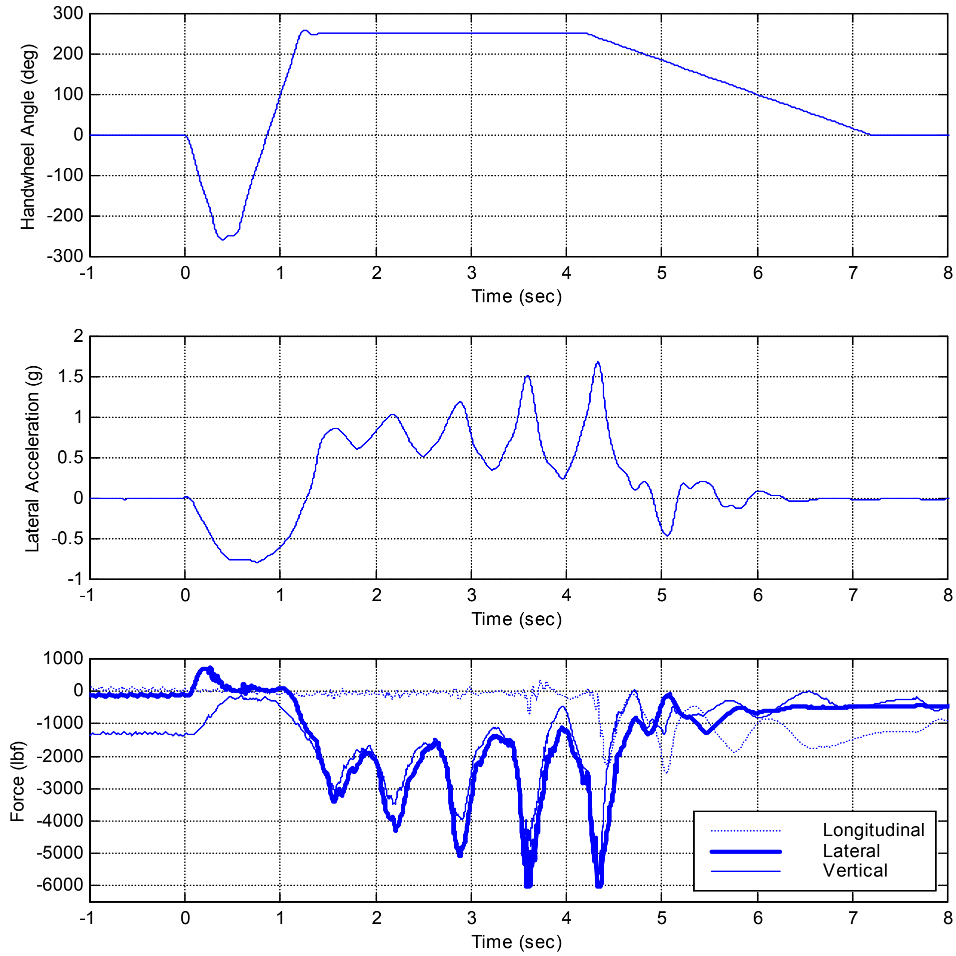

Figure 9.7. Lateral acceleration and wheel force data observed during a left-right Fishhook 1b test performed with the Mercedes ML320 in the Nominal Load configuration with stability control using a six-component wheel load transducer. Left front rim-to-pavement contact occurred during the fourth and fifth roll oscillations.

9.6.3 Effect of Stability Control on Two-Wheel Lift

The Toyota 4Runner and Mercedes ML320 allowed comparisons to be made (on a per vehicle basis) between tests with enabled *and* disabled stability control. The following discussion provides a lateral acceleration, yaw rate, roll angle, and roll rate response comparison of tests performed with both vehicles.

9.6.3.1 Mercedes ML320

Figure 9.8 presents three right-left Fishhook 1b maneuvers performed with the Mercedes ML320 in the Nominal Load configuration. The figure includes a test performed at 46.4 mph with disabled stability control, the lowest speed for which two-wheel lift occurred in this configuration with the ML320.

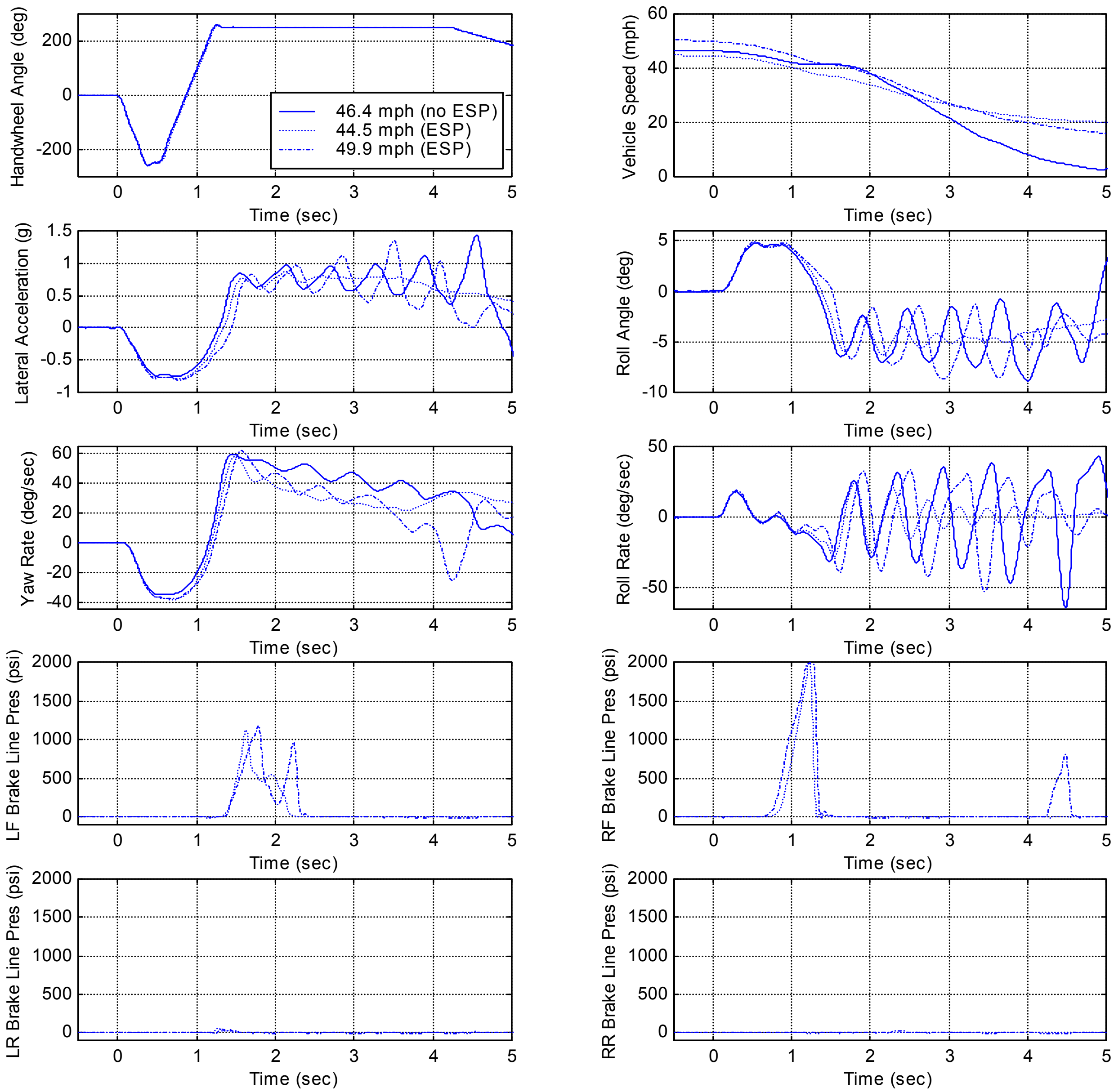

Figure 9.8. Fishhook 1b inputs and outputs for Mercedes ML320 tests performed with enabled and disabled stability control in the Nominal Load configuration. Two-wheel lift occurred during the fifth and sixth roll oscillations for the test begun at 46.4 mph with disabled stability control, and during the third oscillation for the test begun at 49.9 mph with enabled stability control.

Tests performed with enabled stability control in Figure 9.8 had maneuver entrance speeds of 44.5 and 49.9 mph. The 49.9 mph entrance speed was the lowest for which two-wheel lift occurred with the ML320 in this configuration. The 44.5 mph test did not produce two-wheel lift. It is shown only to demonstrate how stability control affected the vehicle during a test performed with an entrance speed similar to that producing two-wheel lift with disabled stability control.

For the tests shown in Figure 9.7, stability control intervention occurred during both tests with it enabled. In each test, brake torque was applied first to the right front, then to the left front, wheel of the vehicle in an attempt to correct what the stability control system interpreted as excessive oversteer induced by the initial steer and countersteer inputs, respectively.

For the test performed at 44.5 mph, braking of the right front wheel first occurred 0.74 seconds after the steering input began (0.21 seconds after the reversal was initiated), and lasted approximately 0.57 seconds. When compared to the test performed at 46.4 mph with disabled stability control, the effect of this intervention was not apparent. Although the peak lateral acceleration and yaw rate produced by the initial steer were greater than those produced during the 46.4 mph test with disabled stability control, it is doubtful stability control intervention was responsible for these differences. Given that these peaks occurred at or slightly before the onset of intervention, these differences are most likely attributable to test-to-test output variability.

The second intervention for the test performed at 44.5 mph involved braking of the left front wheel, and occurred 1.33 seconds after the initial steer was input (0.80 seconds after the reversal began). This intervention had some effect in dampening the roll motion of the vehicle. When compared to the test performed at 44.5 mph with disabled stability control, roll oscillations were of somewhat lesser magnitude.

The most pronounced effect of the intervention that occurred during the test performed at 44.5 mph was how it affected the yaw rate of the vehicle after the steering reversal was input. The suppression of excessive yaw directly affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were utilized, the exit speed of the maneuver with an entrance speed of 44.5 mph with enabled stability control was greater than that of the test begun at 46.4 mph with disabled stability control.

When an entrance speed of 49.9 mph was used during enabled stability control tests, the responses of the ML320 were similar to those occurred produced during the disabled stability control test initiated at 46.4 mph. In this case, braking first occurred 0.65 seconds after the initial steering input (0.15 seconds after the reversal began), and lasted approximately 0.71 seconds. When compared to the test performed at 46.4 mph with disabled stability control, the effect of this intervention appears to be an initial slowing of the vehicle's lateral acceleration and roll responses.

The second intervention for the test performed at 49.9 mph occurred 1.37 seconds after the initial steer was input (0.86 seconds after the reversal was initiated). As stability control intervention transitioned from braking of the right front wheel to the left front wheel, the lateral acceleration and roll responses of the vehicle increased at a rate greater than that for the other tests shown in Figure 9.12. Intervention was unable to effectively dampen the subsequent roll motion of the vehicle. Local lateral acceleration and roll angle peaks increased with each oscillation. Two-wheel lift was produced during the third peak, and the left front tire debeaded at approximately the time of the fifth peak. When compared to the test performed at 46.4 mph with disabled stability control, two-wheel lift was produced two oscillations sooner (the test performed at 46.4 mph produced two-wheel lift at approximately the fifth and sixth roll peaks). With the exception of the first two post-reversal lateral accelerations peaks, the peak values of the test performed at

49.9 mph with enabled stability control were greater than those produced during the 46.4 mph test with disabled stability control through the first four roll oscillations.

In agreement with the test performed at 44.5 mph, the most pronounced effect of stability control intervention during the test performed at 49.9 mph was in correcting the yaw rate of the vehicle after the steering reversal was input. The reduction of excessive yaw rate again affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Although multiple brake applications were utilized, the exit speed of the maneuver begun at 49.9 mph with enabled stability control was greater than the one begun at 46.4 mph with disabled stability control.

9.6.3.2 Toyota 4Runner

Figure 9.9 presents three left-right Fishhook 1b maneuvers performed with the Toyota 4Runner in the Reduced Rollover Resistance configuration. The figure includes a test performed at 37.7 mph with disabled stability control, the lowest speed for which two-wheel lift was occurred in this configuration with the 4Runner. The tests performed with enabled stability control had maneuver entrance speeds of 40.3 and 49.6 mph. The 49.6 mph entrance speed was the lowest for which two-wheel lift was occurred with the 4Runner in this configuration. The 40.3 mph test did not produce two-wheel lift. It is shown only to demonstrate how stability control affected vehicle response by presenting a test performed with an entrance speed similar to that producing two-wheel lift with disabled stability control.

For the tests shown in Figure 9.9, stability control intervention was detected during both tests for which it was enabled. In each case, brake torque was applied first to the left front and rear, then to the right front and rear of the vehicle in an attempt to correct what the stability control system interpreted as excessive oversteer conditions induced by the initial steer and countersteer inputs, respectively.

For the test performed at 40.3 mph, braking of the left wheel first occurred 0.32 seconds after the steering input began (0.24 seconds *before* the reversal was initiated), and lasted approximately 1.02 seconds. This action was almost immediately supplemented with light left and right rear wheel braking that occurred 0.45 seconds after steering was first initiated (0.11 seconds *before* the reversal began). Both rear brake applications lasted until the maneuver was complete. When compared to the test performed at 37.7 mph with disabled stability control, the effect of this intervention was not apparent.

The second intervention of the test performed at 40.3 mph involved left front wheel braking and occurred 1.12 seconds after steering was first initiated (0.62 seconds after the reversal began). Braking of the left front wheel lasted for much of the rest of the maneuver (1.88 seconds). Stability control intervention appears to have suppressed some roll motion of the vehicle, however, oscillations were still evident. When compared to the test performed at 37.7 mph with disabled stability control, these oscillations were of lesser magnitude.

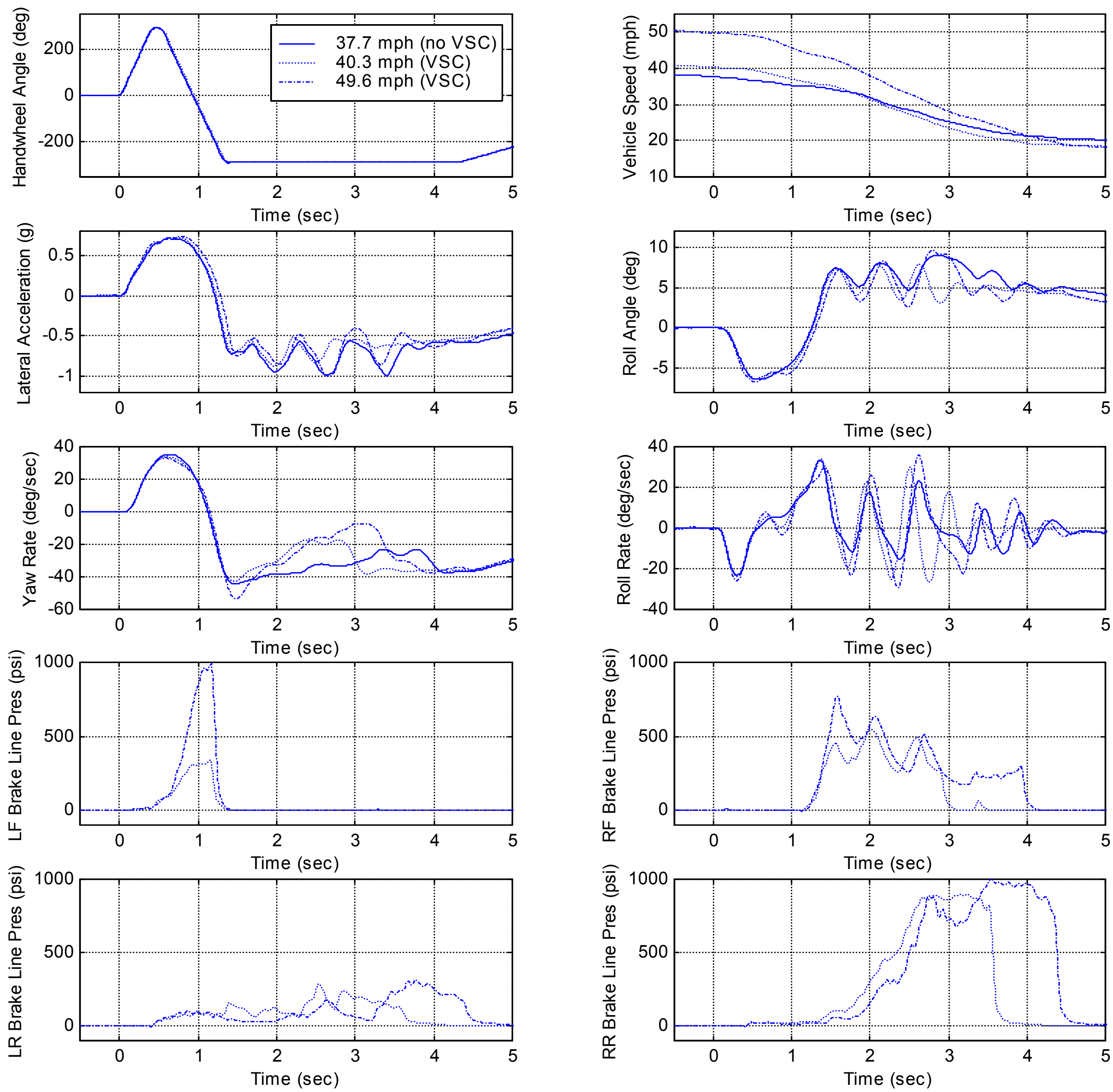

Figure 9.9. Fishhook 1b inputs and outputs for Toyota 4Runner tests performed with enabled and disabled stability control in the Reduced Rollover Resistance configuration. Two-wheel lift occurred during the third roll oscillation for the test begun at 37.7 mph with disabled stability control *and* for the test begun at 49.6 mph with enabled stability control.

In agreement with the Mercedes ML320 results, the most pronounced effect of the intervention that occurred during the test performed at 40.3 mph was how it affected the yaw rate of the vehicle after the steering reversal was input. The suppression of excessive yaw directly affected the manner in which vehicle speed was scrubbed-off throughout the maneuver. Unlike what happened in the ML320 example shown in Figure 9.8, the exit speed of the test begun at 40.3 mph with enabled stability control was *less* than begun at 37.7 mph with disabled stability control. The peak post-reversal yaw rate magnitudes of these tests were nearly equal.

When an entrance speed of 49.6 mph was used during enabled stability control tests, the responses of the 4Runner were more similar to those produced during the disabled stability control test initiated at 37.7 mph than to those produced at 40.3 mph with enabled stability control. In this case, left front braking first occurred only 0.23 seconds after the initial steer input began (0.30 seconds *before* the reversal was initiated), and lasted approximately 1.15 seconds. This action was almost immediately supplemented with light left and right rear wheel braking that occurred 0.45 seconds after steering was first initiated (0.09 seconds *before* the reversal began). Both rear brake applications lasted until the maneuver was complete. Other than a slight slowing of the lateral acceleration response to the initial steer, the effects of this intervention was not apparent (when compared to the test performed at 37.7 mph with disabled stability control).

The second intervention of the test performed at 49.6 mph began with braking of the left front wheel 1.21 seconds after the initial steer was input (0.67 seconds after the reversal was initiated). This action lasted until the maneuver was complete. In this case, intervention was unable to effectively dampen the roll motion of the vehicle. Lateral acceleration and roll angle peaks increased with each oscillation until two-wheel lift was produced. Two-wheel lift was produced during the third roll oscillation. Compared to the test performed at 37.7 mph with disabled stability control, the lateral acceleration and roll angle oscillations were of similar magnitude. Peak roll rates during the test performed at 49.6 mph with enabled stability control were generally greater than for most of the peaks produced during the test performed at 37.7 mph with disabled stability control

In agreement with the enabled stability control test performed at 40.3 mph, the most pronounced effect of stability control intervention during the test performed at 49.6 mph was in correcting the yaw rate of the vehicle after the steering reversal was input. That said, the peak yaw rate of this test was approximately 23 percent greater than for either of the two other tests shown in Figure 9.9. The attempt by the 4Runner's stability control system to suppress excessive yaw affected the manner in which vehicle speed was scrubbed throughout the maneuver. The exit speed of both tests performed with stability control was *less* than that of the test begun at 37.7 mph with disabled stability control.

9.6.4 Ability of Roll Rate Feedback to Adapt to Different Vehicle Configurations

Roll rate feedback was able to successfully adapt Fishhook 1b dwell times to the different test vehicle configurations. This is best illustrated by considering tests performed with the Toyota 4Runner and Chevrolet Blazer. Although each of the Phase IV vehicles was evaluated with three loading configurations using Fishhook 1b, the 4Runner and Blazer used rear-mounted ballast in their respective Modified Handling configurations. Rear-mounted ballast affected each vehicle's performance to a greater extent than the optional wheel/tire packages used in the Ford Escape and Mercedes ML320 Modified Handling configurations.

9.6.4.1 Toyota 4Runner

Figures 9.10 and 9.11 present the handwheel dwell times measured during all valid Fishhook 1b tests performed with the Toyota 4Runner. Tests performed with stability control enabled (Figure 9.10) and disabled (Figure 9.11) are provided for each loading configuration. The range of dwell times in the Nominal Load configuration was 55 to 95 ms with enabled stability control and 40 to 90 ms with disabled stability control. In the Reduced Rollover Resistance configuration, the range of dwell times in the with enabled and disabled stability control were 85 to 130 ms and 105 to 160 ms, respectively. The range of dwell times in the Modified Handling configuration was 180 to 575 ms with enabled stability control and 315 to 675 ms with disabled stability control.

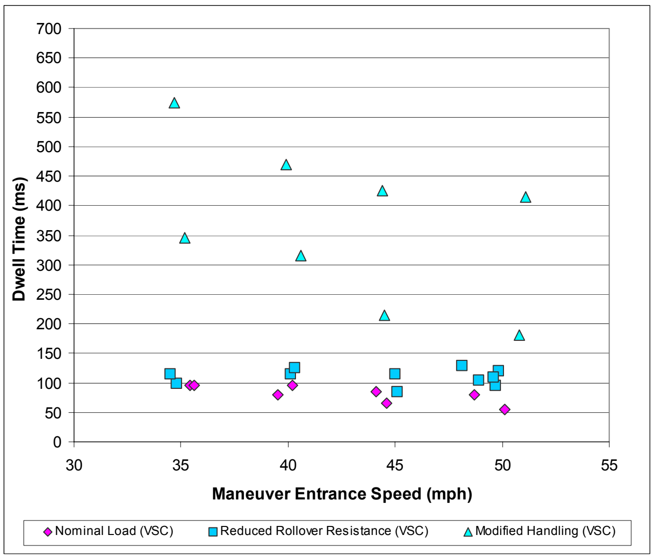

Figure 9.10. Dwell times during Fishhook 1b tests performed with the Toyota 4Runner (enabled VSC).

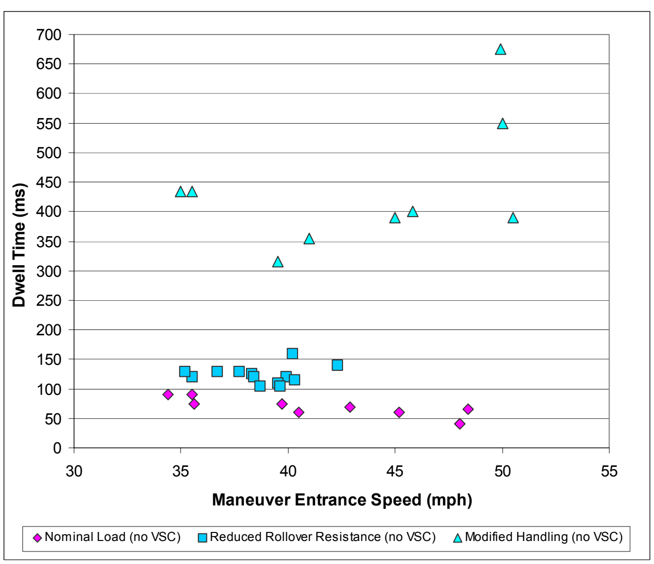

Figure 9.11. Dwell times during Fishhook 1b tests performed with the Toyota 4Runner (disabled VSC).

9.6.4.2 Chevrolet Blazer

Figure 9.12 presents the handwheel dwell times measured during all valid Fishhook 1b tests performed with the Chevrolet Blazer. Tests performed with stability control enabled and disabled are provided for each loading configuration. The range of dwell times in the Nominal Load configuration was 15 to 40 ms. In the Reduced Rollover Resistance configuration, the range of dwell times was 45 to 70 ms. The range of dwell times in the Modified Handling configuration was 125 to 200 ms.

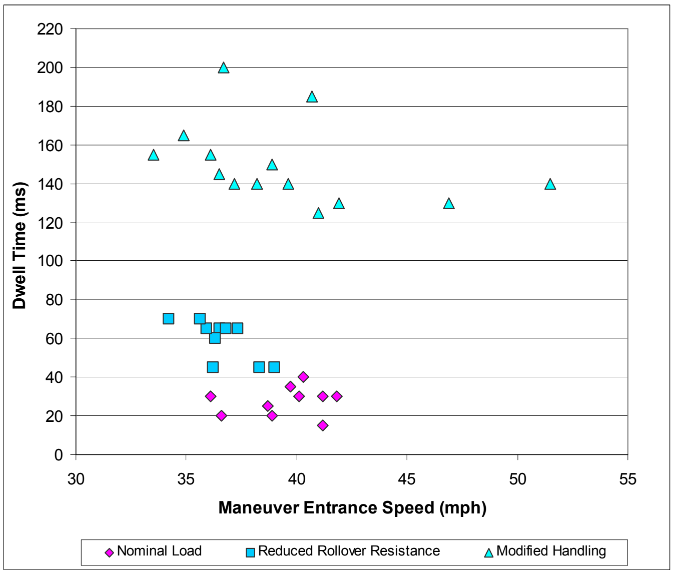

Figure 9.12. Dwell times during Fishhook 1b tests performed with the Chevrolet Blazer.

9.6.5 Extended Dwell Times

During Phase III-A, it was discovered that certain fishhook handwheel combinations, input at certain vehicle speeds, could produce unexpectedly long dwell times when performed with roll rate feedback. Although improper functionality of the roll rate feedback feature was initially suspected, comparison of the instant the roll rate signal first entered the steering machine's window comparator and the instant the handwheel reversal was initiated were found to be in good agreement.

The cause of these apparently anomalous test outcomes was traced back to the test vehicle's actual roll response. During tests for which extended dwell times were evident, after the initial roll rate peak (in response to the initial steer), the magnitude of the roll rate decreased substantially but not enough to enter the comparison window. (For "typical" tests (i.e., the Phase III-A tests without extended dwell times), the roll rate crosses zero following the initial peak.) This is thought to be due to the second vibrational roll mode of the vehicle[3]. This caused the

[3] Ed Heitzman pointed out that the second vibrational roll mode of the vehicle could cause this behavior in an oral presentation made to the SAE Vehicle Dynamics Committee in March 2002.

handwheel dwell time to be extended beyond that of other, similar, tests. Eventually the maximum roll angle was achieved and the handwheel reversal occurred. By this time, considerable yaw had built up, and the reversal affected the performance of the vehicle in a different manner than during other tests performed in the series. That said, the amount of two-wheel lift with and without extended dwell times was in good agreement (for tests begun at nearly equal maneuver entrance speeds).

Long handwheel dwell times again occurred during the Phase IV testing. Rather than being induced by a certain combinations of handwheel rates and magnitudes, however, they were the result of how the rear-mounted ballast used in the Modified Handling configuration with the Toyota 4Runner and Chevrolet Blazer influenced test vehicle roll response. Due to the weight of the rear-mounted ballast, roll responses slowed substantially. As a result, it took longer for the vehicles equipped with rear-mounted ballast to achieve their maximum roll angle in response to the initial steering input.

Anomalous dwell times did not occur during any valid Phase IV Fishhook 1b test. The extended dwell times in Phase IV were legitimate adaptations commanded by the steering machine to maximize roll motion during tests performed with rear ballast.

The largest Fishhook 1b dwell time in Phase IV was recorded with the Toyota 4Runner in the Modified Handling configuration with disabled stability control (675 ms). This was 360 ms longer than the shortest dwell time recorded for the 4Runner in this series (315 ms). Figure 9.13 presents the inputs and outputs associated with these tests. In both cases, the steering reversals were appropriate and occurred at times that maximized the vehicle's roll motion. Note that the vehicle was unable to respond to the reversal following the 675 ms dwell time due to a spin-out. This test was performed with an entrance speed of 49.9 mph.

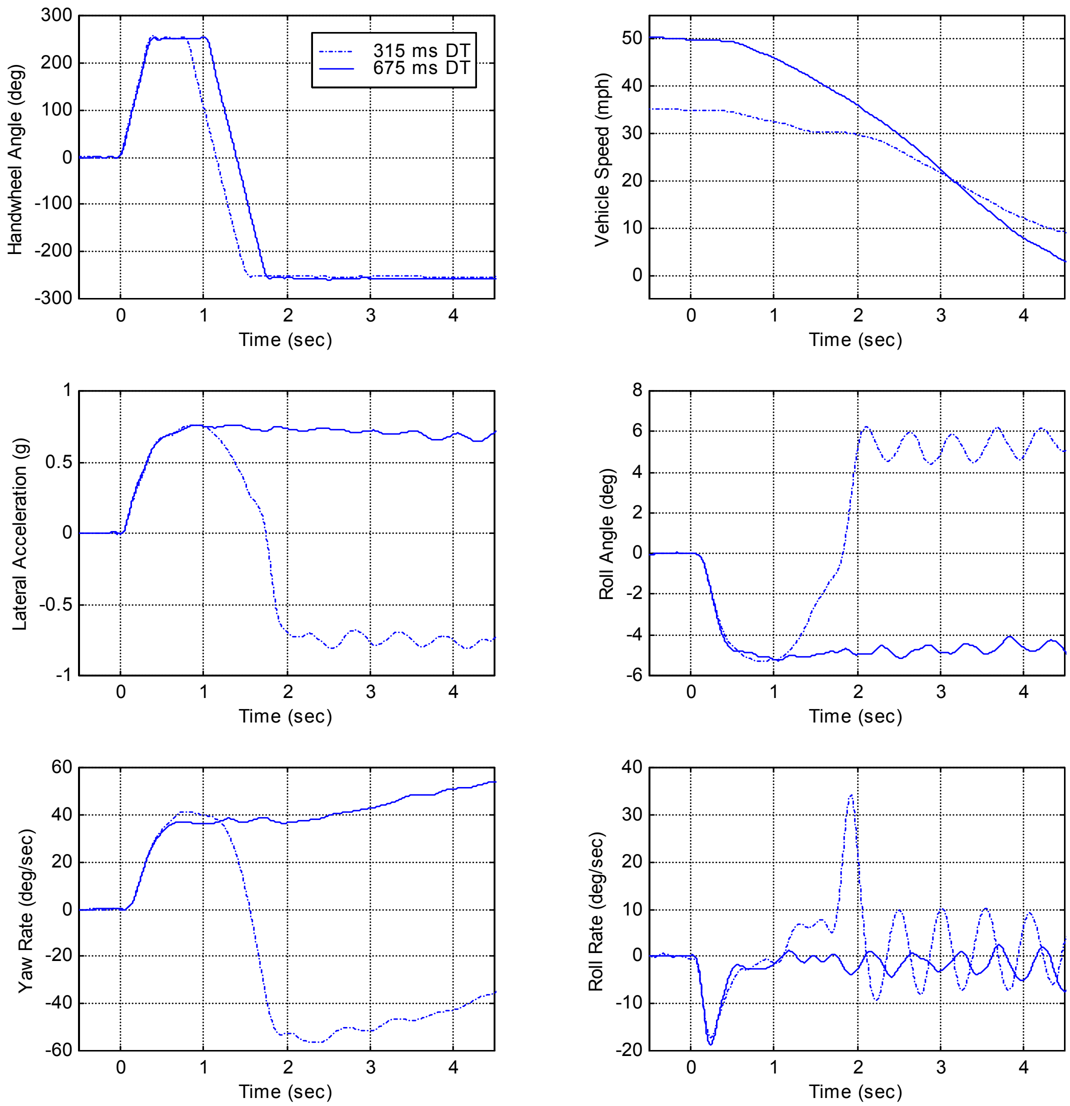

Figure 9.13. Fishhook 1b inputs and outputs for two tests performed with the Toyota 4Runner in the Modified Handling configuration (disabled stability control).

9.7 Fishhook 1b Maneuver Assessment

Using the evaluation factors presented in Chapter 2, the authors have rated the Fishhook 1b maneuver in the following manner:

Objectivity and Repeatability = Excellent

Fishhook 1b was performed with good to excellent objectivity and repeatability. By using the programmable steering machine, handwheel inputs were precisely executed, and able to be replicated from run-to-run. Test drivers were able to achieve maneuver entrance speeds an average of ± 1.3 mph from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data during Fishhook 1b tests were highly repeatable. That said, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, lower than that at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of Fishhook 1b maneuver.

The Objectivity and Repeatability of the Fishhook 1b maneuver is slightly worse than that of Fishhook 1a. This is because using roll rate feedback to initiate fishhook steering reversals can increase dwell time variability when certain combinations of handwheel angles, rates, and vehicle speed are input together (as discussed in the Phase III-A Technical Report, [7]). Such combinations can influence the roll motion of the vehicle such that it differs from that observed during other tests performed in a particular series. Since the roll rate zero crossing immediately following completion of the initial steer defines when the handwheel reversal is initiated, a delayed roll rate zero crossing translates into an extended dwell time. If this occurs, preservation of the vehicle's roll motion can be compromise (even though the reversal still occurs when the vehicle achieves its post-initial steer maximum roll angle).

No anomalous roll rate zero crossings or inappropriately extended dwell times occurred during any valid Fishhook 1b test performed in Phase IV. However, the potential for such occurrences does exist. Efforts to prevent this phenomenon from influencing future test results are presently under development.

While the authors acknowledge the existence of this issue, the effect happens quite rarely, and it is obvious to the test driver when this delay causes the need to repeat a test run. Therefore, from a practical point of view, the objectivity and repeatability of this maneuver is not much worse from that of Fishhook 1a. As a result, the authors assigned this maneuver the same Objectivity and Repeatability rating as for the Fishhook 1a, Excellent.

Performability = Excellent

Objective and repeatable Fishhook 1b maneuvers were easily performed with the programmable steering controller. The test procedure was well developed and adapted handwheel input magnitudes to the vehicle being evaluated. Use of roll rate feedback allowed the timing of Fishhook 1b handwheel inputs (the duration of the dwell time) to automatically adapt to a given set of test conditions (e.g., maneuver entrance speed, load configuration, stability control intervention) on a test-to-test basis.

Discriminatory Capability = Excellent

Fishhook 1b is an excellent maneuver for measuring the rollover resistance of different vehicles. Two-wheel lift was produced during tests performed with the Chevrolet Blazer and Mercedes ML320 (with enabled and disabled stability control) in the Nominal Load configuration. Each

Phase IV vehicle tested in the Reduced Rollover Resistance configuration experienced two-wheel lift, regardless of whether its stability control was enabled or disabled (if so equipped).

Although the Mercedes ML320 was not evaluated in the Reduced Rollover Resistance configuration, the authors are certain it would have been exhibited two-wheel lift during tests performed in the this configuration. Reduced Rollover Resistance configuration raises a vehicle's center of gravity height. This action will encourage, not prevent, two-wheel lift.

While Fishhook 1b does an excellent job of discriminating between different levels of untripped rollover resistance for typical, current generation, sport utility vehicles, it is unlikely the maneuver will be capable of such discrimination for the entire light vehicle fleet. The authors do not anticipate many two-wheel lifts will occur during testing of vehicles that have a Static Stability Factors of 1.13 or greater (e.g., vehicles that earn three or more stars under NHTSA's current rollover rating program). That said, Fishhook 1b is one of only two maneuvers known to NHTSA to cause two-wheel lifts for vehicles in the above 1.13 SSF range (e.g., for the Mercedes ML320). Therefore, the Fishhook 1a maneuver does as good a job of discriminating throughout the entire fleet of vehicles as will any other on-road, untripped Rollover Resistance maneuver if the occurrence of two-wheel lift is used as a criterion.

Appearance of Reality = Excellent

The handwheel inputs defining any fishhook maneuver approximate the steering a driver might use in an effort to regain lane position on a two-lane road after dropping the two passenger-side wheels off onto the shoulder.

10.0 NISSAN FISHHOOK

Conceptually similar to NHTSA's Fishhook 1b maneuver, the Nissan Fishhook also seeks to maximize maneuver severity by maximizing the roll motion of the vehicle being evaluated. Whereas the Fishhook 1b methodology commands handwheel reversals to occur at maximum roll angle, the Nissan approach relies on a four-part method that iteratively determines the appropriate dwell time for a particular range of vehicle speeds. Because these dwell times were determined via iteration, not direct feedback, the Nissan Fishhook is considered to be an open-loop maneuver.

The Nissan methodology compared vehicle responses produced with two maneuvers. The first was a step steer similar to NHTSA's J-Turn. The second maneuver was a fishhook. The dwell time of the fishhook was iteratively adjusted until the third roll rate zero crossing produced during the step steer occurred within 50 milliseconds of the first lateral acceleration zero crossing produced during the fishhook. If the lateral acceleration zero crossing occurred more than 50 milliseconds before the third roll rate zero crossing, the dwell time before the countersteer input was increased. Conversely, if the difference was greater than 50 milliseconds, the dwell time was reduced.

All tests related to the Nissan Fishhook were performed in the Nominal Load configuration. Only the Chevrolet Blazer and Ford Escape were evaluated using this maneuver.

This chapter is comprised of seven sections. Section 10.1 describes the maneuver and how it was executed. Section 10.2 and 10.3 discuss the steering and vehicle speed input repeatability, respectively. Section 10.4 discusses maneuver entrance speed input variability. Section 10.5 discusses output repeatability. Section 10.6 presents test results. Section 10.7 provides a maneuver assessment and concluding remarks.

10.1 Nissan Fishhook Maneuver Description

10.1.1 Handwheel Inputs

The Nissan Fishhook uses a four-part procedure to iteratively determine the appropriate dwell time for a particular range of vehicle speeds.

Part 1

Part 1 of the Nissan Fishhook was to determine the time of the third roll rate zero-crossing during a step steer maneuver at a selected maneuver entrance speed. This test was performed similarly to the NHTSA J-Turn maneuver except that the handwheel steering magnitude and rate were always 270 degrees and 1,080 degrees per second, respectively. Using data produced by this test, the time of the third roll rate zero crossing, measured from initiation of steering, was determined. Figure 10.1 presents handwheel position and roll rate data from two step steer tests, one run using the Ford Escape and the other run using the Chevrolet Blazer. Note the excellent handwheel repeatability of the inputs.

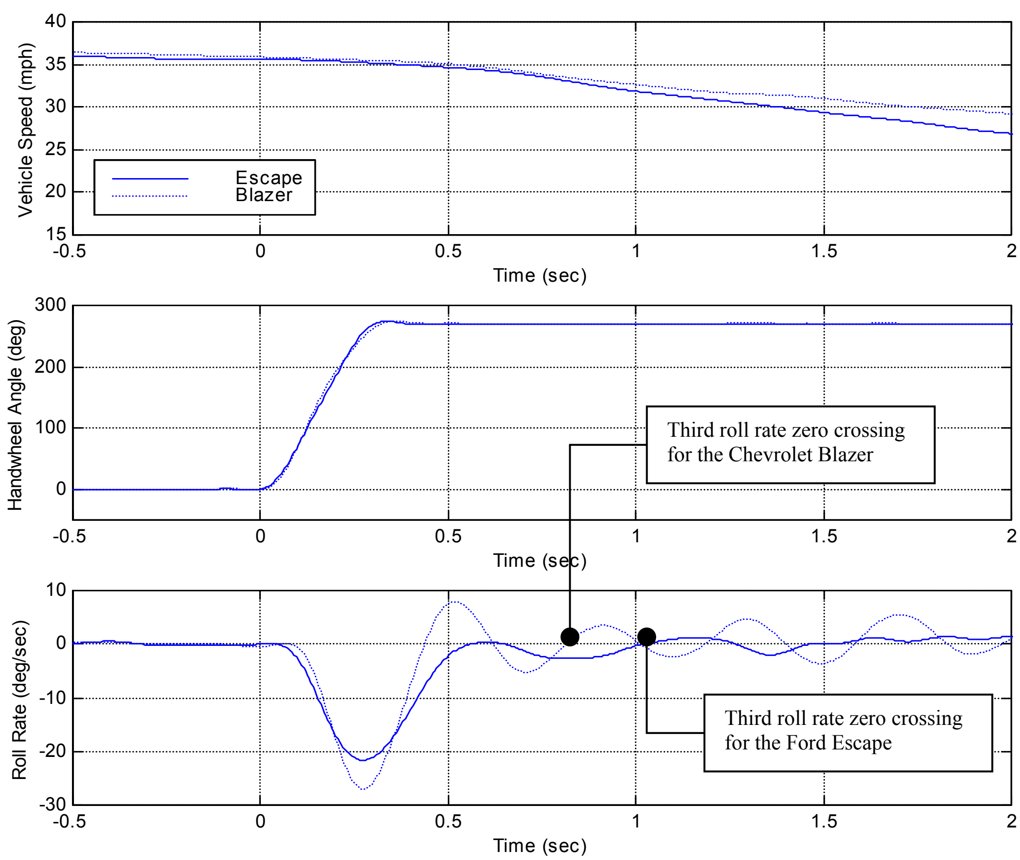

Figure 10.1. Handwheel position and roll rate data from two step steer tests, one performed with the Ford Escape and the other with the Chevrolet Blazer.

Part 2

For Part 2 of the Nissan procedure a fishhook test was performed using a steering input with zero dwell time. The initial handwheel steering magnitude and rate for this test were identical to those of the Part 1 step steer test (270 degrees and 1,080 degrees per second, respectively). Although the rate of the reversal remained at 1,080 degrees per second, its magnitude was vehicle dependent. Reversal magnitude was defined as from the initial 270 degrees in one direction to 45 degrees less than the handwheel position at full steering lock in the opposite direction. Using data produced by this input, the time of the first lateral acceleration zero crossing, measured from initiation of the maneuver, was determined. Figure 10.2 presents handwheel position and lateral acceleration data from two zero dwell time fishhooks, one run using the Ford Escape and the other run using the Chevrolet Blazer.

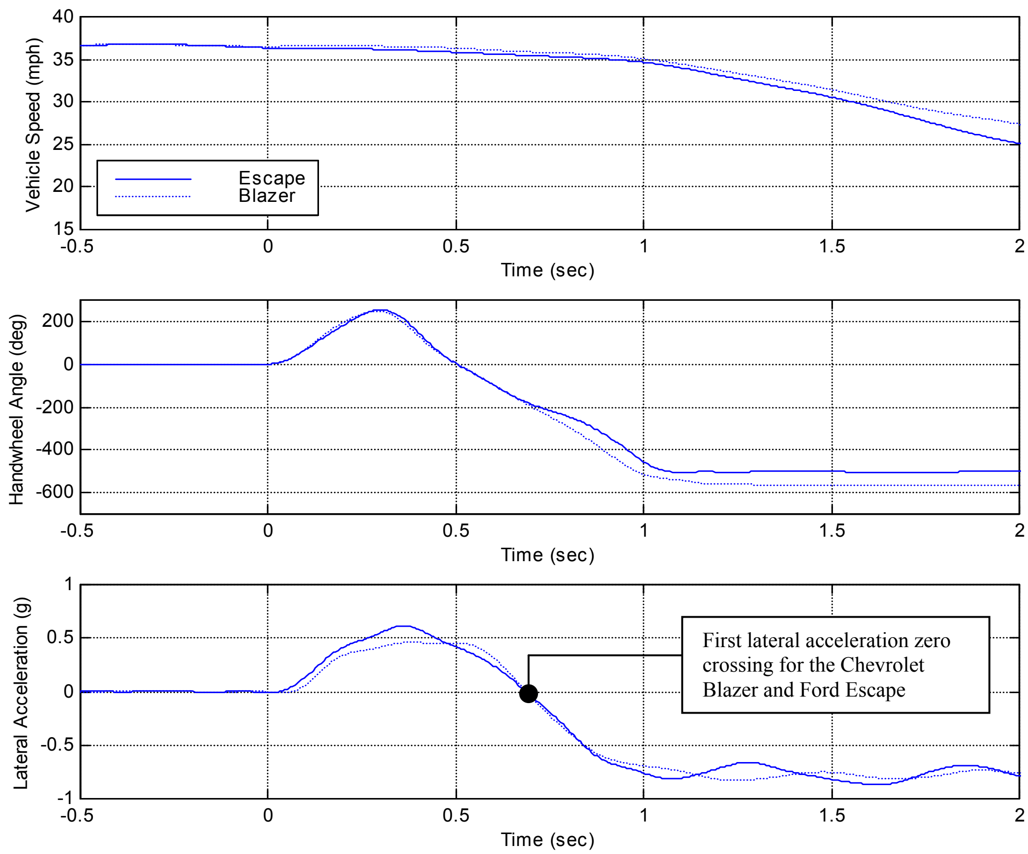

Figure 10.2. Handwheel position and lateral acceleration data from two zero dwell time fishhooks, one performed with the Ford Escape and the other with the Chevrolet Blazer.

Part 3

Part 3 of the procedure was to determine the appropriate fishhook dwell times based on comparison of the third roll rate zero crossings (produced with Part 1 step-steer inputs) and the first post-reversal zero crossing (produced with Part 2 fishhook inputs). For any given speed, these key data points were not to differ by more than 50 milliseconds. Using the results of Part 2 to estimate what values might be appropriate, dwell times were iteratively adjusted so as to achieve the desired roll rate versus lateral acceleration relationship. This iterative process was performed with attention to the number of tests performed on a given tire set. The authors agreed with Nissan's recommendation of an eleven test maximum (per direction of steer), and it served as a guide that was used to schedule tire replacements for tests related to the Nissan Fishhook.

Figure 10.3 presents Nissan Fishhook examples for the Ford Escape and the Chevrolet Blazer. The dwell times of both maneuvers were defined in accordance with the Nissan methodology. Note the phasing of the third roll rate zero crossing produced with the step-steer, and the first lateral acceleration zero crossing produced with the fishhook.

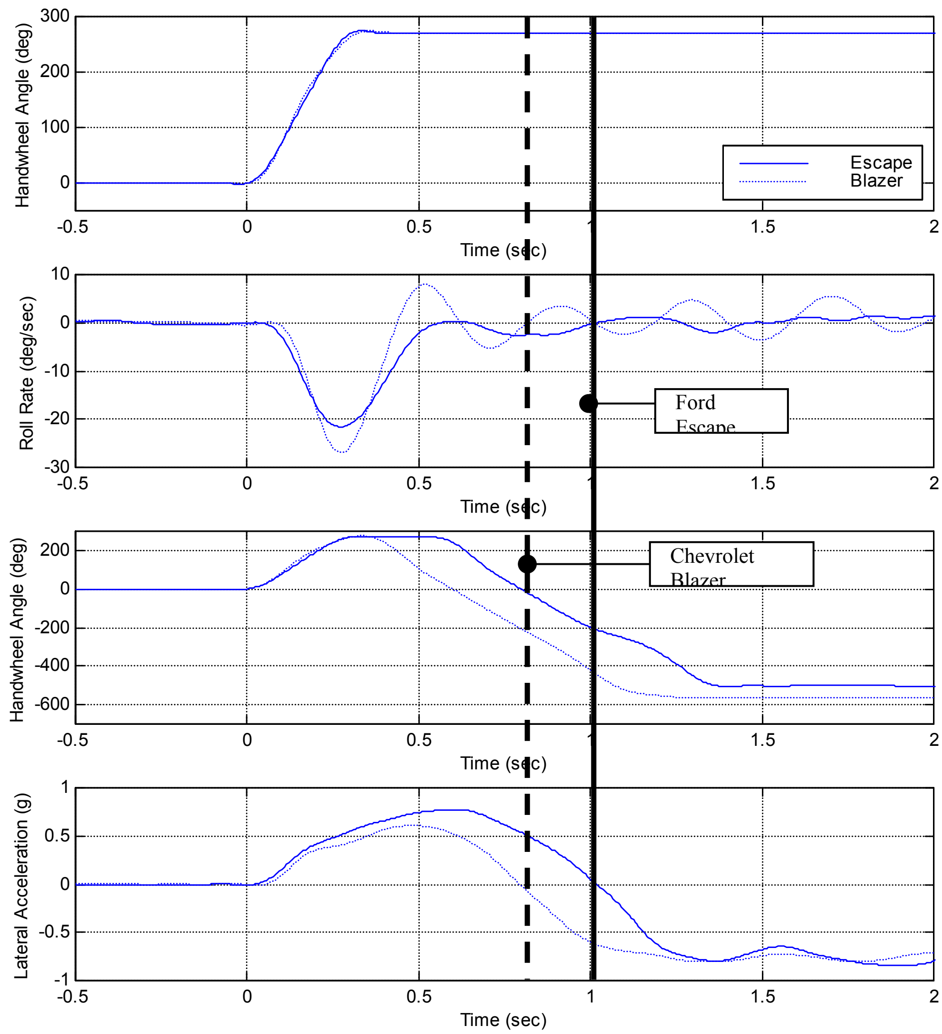

Figure 10.3. Handwheel position and vehicle response data from Nissan Fishhooks performed with the Ford Escape and the Chevrolet Blazer. Correct dwell time specification insured the relationship between the step steer roll rate and fishhook lateral acceleration was appropriate.

Part 4

Using the dwell times established in Part 3, the final, actual, tests series were performed. Table 10.1 presents the Nissan Fishhook handwheel inputs used in Phase IV. A discussion of the maneuver entrance speeds is provided in the next subsection.

Table 10.1. Phase IV Nissan Fishhook Maneuver Handwheel Input Magnitudes.

Vehicle	Initial Steer (deg)	Reversal (deg)	Rate (deg/sec)	Dwell Time (ms)			
				Commanded	Actual		
					Range	Average	Standard Deviation
Chevrolet Blazer	270	570	1080	100	20 - 55	38	12.5
Ford Escape	270	505	1080	300	215 - 255	233	14.4

The actual Nissan fishhook dwell times are shorter than the commanded dwell times. From Table 10.1, the average dwell time for the Chevrolet Blazer was 62 milliseconds shorter than commanded while for the Ford Escape the average dwell time was 67 milliseconds shorter.

To determine the reason for this discrepancy, one steering angle trace was examined in detail. The problem turns out to be that the steering requirements of the Nissan Fishhook were slightly beyond the capabilities of the steering machine.

Ideally, the handwheel steering angle would go from 0 to 270 degrees in 250 milliseconds at a constant rate of 1,080 degrees per second. In actuality, time is required to accelerate to a steady state steering rate at the start of steering and again to decelerate at the completion of steering. For the test examined, the handwheel steering rate took 100 milliseconds to attain its steady state value. During this time, the steering angle went from 0 to 50 degrees. This was 58 degrees less than the ideal steering angle 100 milliseconds after the initiation of steering.

The steady state steering rate attained was 1,160 degrees per second. Since this was slightly greater than the nominal 1,080 degrees per second, the actual steering wheel angle partially caught up to the ideal angle. The steady state steering rate was maintained for 155 milliseconds. At the end of this steady state period the actual steering wheel angle was 230 degrees, 40 degrees less than the 270 degrees that should have been reached by this time.

The actual steering then took 65 milliseconds to go from 230 to 270 degrees with the steering rate slowing from 1,160 to 0 degrees per second. In total, the initial steering movement actually took 320 milliseconds instead of the 250 milliseconds that it was supposed to. Due to the time required to accelerate and decelerate the steering wheel, the steering machine simply could not complete the desired steering movement in the desired time. This delay reduced the dwell time by 70 milliseconds, in close agreement with the values seen in Table 10.1.

In comparison, checking data traces showed that the steering machine could accomplish the Fishhook 1a or Fishhook 1b initial steering movements in closer to the specified time. For the Toyota 4Runner, the Fishhook 1a/1b initial steering movement ideally was from 0 to 287 degrees in 399 milliseconds at a constant rate of 720 degrees per second. For one, typical Toyota 4 Runner test the handwheel steering rate took 50 milliseconds to attain its steady state value. Note that this is only 50 percent of the handwheel steering acceleration time that was needed during the Nissan Fishhook test. This reduced acceleration time occurred because the steady state rate for Fishhook 1a/1b was substantially lower than it was for the Nissan Fishhook. During this time, the steering angle went from 0 to 19 degrees. This was 17 degrees less than the ideal steering angle 50 milliseconds after the initiation of steering.

The steady state steering rate attained was 750 degrees per second. Since this was slightly greater than the nominal 720 degrees per second, the actual steering wheel angle partially caught up to the ideal angle. The steady state steering rate was maintained for 350 milliseconds. At the end of this steady state period the actual steering wheel angle was 282 degrees, 5 degrees less than the 287 degrees that should have been reached by this time.

The actual steering then took 30 milliseconds to go from 282 to 297 degrees with the steering rate slowing from 750 to 0 degrees per second. (While the desired steering angle at the end of the initial steering movement was 287 degrees, the steering machine actually overshot by 10 degrees during this test. The handwheel steering angle returned to 287 degrees during the dwell time.) Again, due to the lower steady state steering rate, this is only 50 percent of the handwheel steering deceleration time that was needed during the Nissan Fishhook test. In total, the initial steering movement actually took 430 milliseconds instead of the 399 milliseconds that it was supposed to. Again, due to the time required to accelerate and decelerate the steering wheel, the steering machine simply could not complete the desired steering movement in the desired time. However, due to the lower steady state steering rate, the discrepancy is about half as large as it was for the Nissan Fishhook.

In a sense, the above discrepancies do not matter. The goal for the Nissan Fishhook was to have the first lateral acceleration zero crossing during the actual maneuver occur within ±50 milliseconds of the third roll rate zero crossing during a previously performed step-steer; this goal was met for all Nissan Fishhook test runs (the maximum discrepancy was ±35 milliseconds). The goal for all three fishhooks to have highly repeatable initial steering movements; this goal was also attained. The slower initial steer rise times that we have seen only matter if tests were performed with two different types of steering machines that had different steering wheel acceleration/deceleration capabilities.

10.1.2 Vehicle Speed

Nissan specified that maneuver entrance speeds begin at 30 mph and be raised in 2 mph increments until the termination speed of 50 mph was reached (tip-up, spin-out, or plow-out were also termination conditions). The 30 mph recommendation was below the lowest entrance speed typically used by NHTSA during rollover propensity maneuvers. As such, the lowest entrance speeds used for the Nissan Fishhook, or any of its components, was 35 mph. Furthermore, the authors believed the 2 mph speed increments to be too fine, and contributed to undesirable tire wear. For this reason, all entrance speed iterations were increased to 5 mph.

10.2 Nissan Fishhook Steering Input Repeatability

The first handwheel ramp of the Nissan Fishhook was identical for each vehicle (magnitude and rate were held constant). The reversal magnitude, however, was vehicle dependent, based on how far the handwheel could be turned before being mechanically governed by the vehicle's steering bumpstop. The fishhook dwell time was vehicle *and speed* dependent, based on the numerous iterations required by the Nissan methodology. Because entrance speed was used as a severity metric for the maneuver, a number of speed iterations were used before a termination condition was realized. Most handwheel inputs remained constant throughout this iterative process, thus providing an opportunity for repeatability assessment.

Although the Nissan methodology had the potential for producing many dwell times (i.e., for specific speeds), tests performed with the Ford Escape and Chevrolet Blazer generally used the same dwell time over the course of their respective test series. As a result, at least four handwheel inputs per vehicle and steering combination were available for comparison. Figure 10.4 presents these data for the Ford Escape. Four right-left steer tests performed in the Nominal Load configuration are represented. The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the individual tests from each other, although some disparity was occurred from approximately 200 to 500 degrees. The cause of this phenomenon is unknown, however the state of charge of the steering machine's 60V power supply is suspect. That said, this disparity was not believed to influence maneuver severity. Note that the ripples immediately after the first handwheel ramp, as well as immediately before the second handwheel ramp, were due to a combination of factors, including the filter applied to the data during post-processing and a slight steering machine input overshoot.

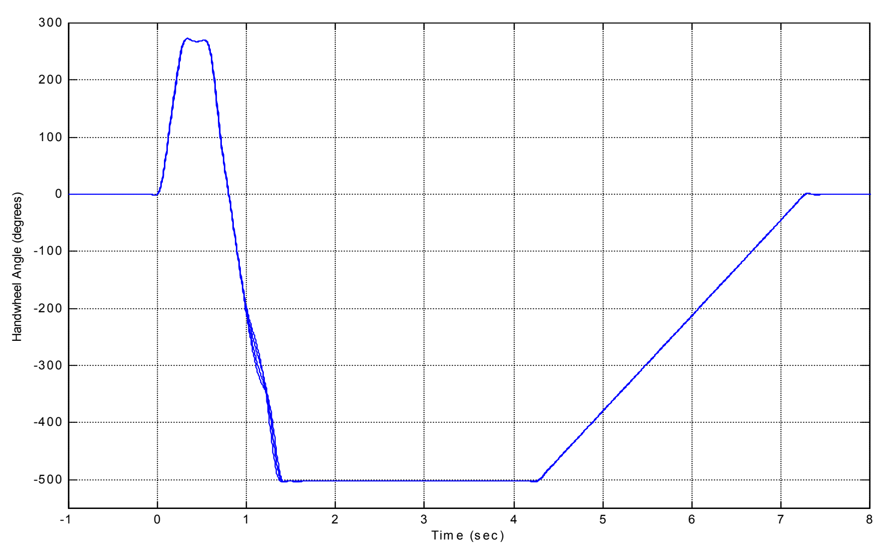

Figure 10.4. Handwheel inputs recorded during four Ford Escape Nissan Fishhook maneuvers.

10.3 Nissan Fishhook Vehicle Speed Repeatability

Figure 10.5 presents handwheel position and vehicle speed data for two Nissan Fishhook tests performed with the Chevrolet Blazer. The data were collected during tests performed at 46.6 and 46.1 mph. Both tests produced two-wheel lift. When the handwheel was returned back to zero degrees following completion of the maneuver, the vehicle speed of the test initiated at 46.6 mph was 17.8 mph, 62 percent lower than that of the entrance speed. A 16.0 mph exit speed was 65 percent lower than that of the entrance speed for the test performed at 46.1 mph. These speed reductions were in agreement with reductions that occurred during Fishhook 1a and 1b tests begun at similar entrance speeds. This comparison is provided in Chapter 18.

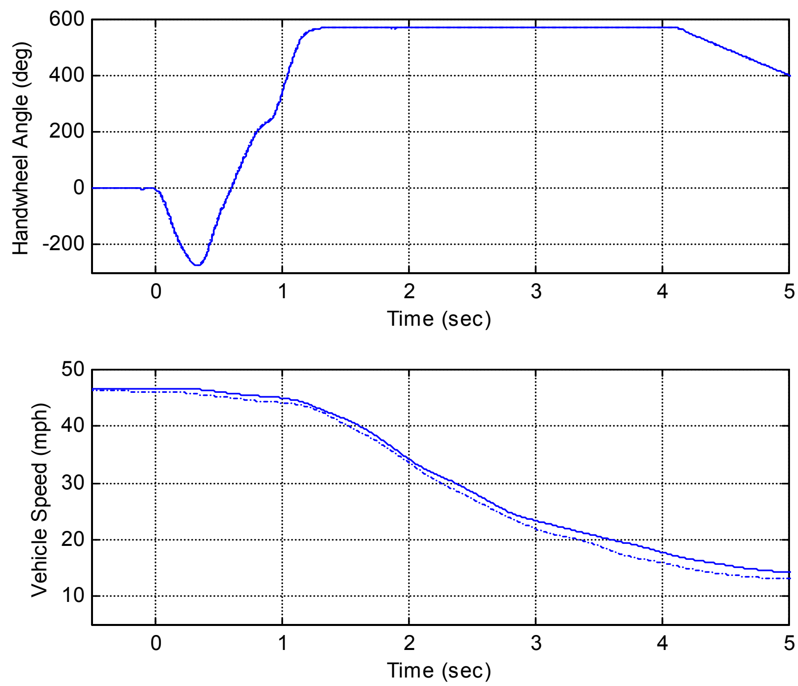

Figure 10.5. Handwheel angle and vehicle speed data for two Nissan Fishhook tests performed with the Chevrolet Blazer.

10.4 Nissan Fishhook Entrance Speed Variability

When all valid Nissan Fishhook tests were considered, for each vehicle in all configurations, the driver was able to achieve entrance speeds within 2.2 mph (6.2 percent) of the desired target speed. The actual and target maneuver entrance speed differed by an average of 0.9 mph (2.2 percent) overall. Fishhook 1b entrance speed variability was in agreement with that of other maneuvers performed with the steering machine.

10.5 Nissan Fishhook Output Repeatability

10.5.1 Test Outputs

The severity metric used for the Nissan Fishhook was vehicle speed. For this reason, data available for the assessment of test output repeatability was limited. If a test produced two-wheel lift during a particular test series, speed was iteratively decreased in approximately 1 mph increments. In some cases, the downward iteration used entrance speeds nearly equivalent to those used in the upward iterations prior to the occurrence of two-wheel lift. If this occurred, test output repeatability could be assessed.

Figure 10.6 presents test outputs for two left-right Nissan Fishhooks performed with the Chevrolet Blazer. The data were collected during tests 1552 and 1553 using entrance speeds of 46.6 and 46.1 mph, respectively. Generally speaking, output repeatability was very good up to the point of two-wheel lift. Test 1552 produced enough wheel lift to contact both left-side outrigger casters, while Test 1553 produced three inches of simultaneous wheel lift without outrigger contact.

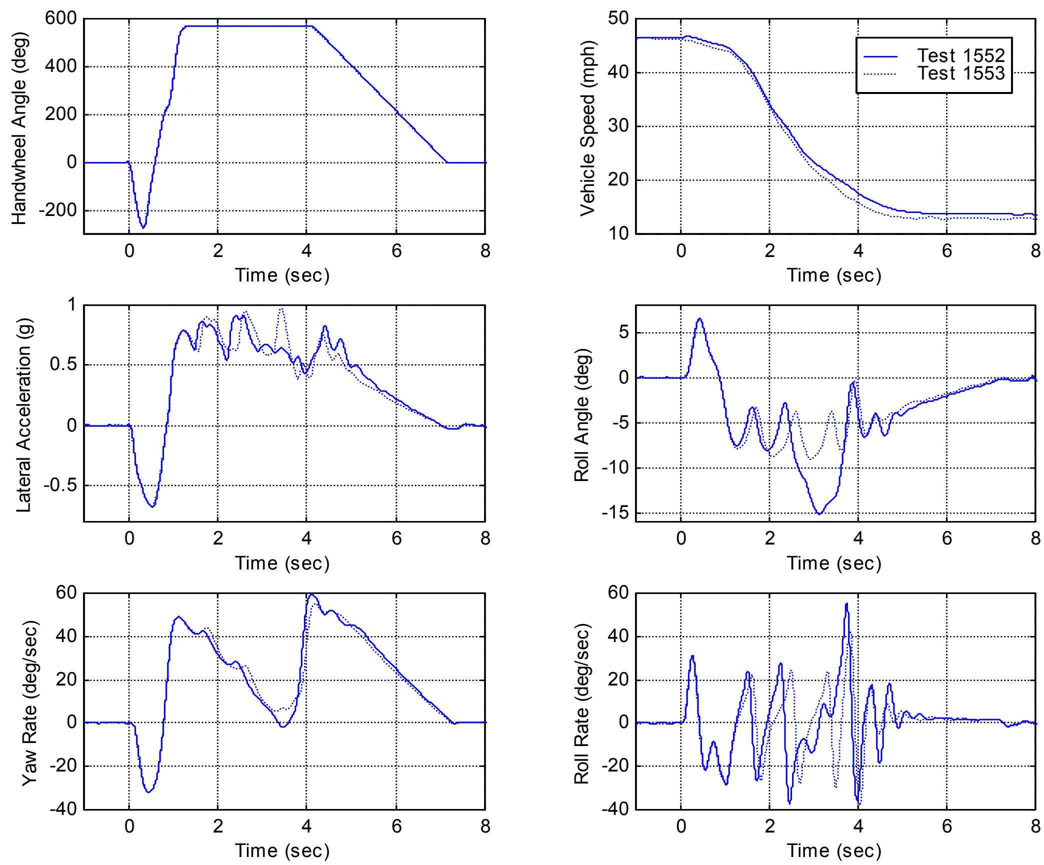

Figure 10.6 Test outputs for two left-right Nissan Fishhooks performed with the Chevrolet Blazer.

At first glance, the roll data presented in Figure 10.6 appears to be very disparate (in a manner similar to the Fishhook 1a data presented previously in Figure 8.4). However, because we are no longer differentiating between moderate and major two-wheel lifts, the differences would not affect the reported results for this maneuver. Therefore, these two tests would give rollover propensity metrics that are in very good agreement (the entrance speeds of the tests in Figure 10.6 differed by only 0.5 mph, and they both produced at least two inches of simultaneous two-wheel lift). The large difference between their roll angle traces occurs because near the initiation of two-wheel lift, the roll angle becomes mathematically unstable; the vehicle either falls over or it does not. As was discussed above for the NHTSA J-Turn, this roll angle non-repeatability occurs for all maneuvers that generate two-wheel lift.

10.5.2 Test Methodology

In general, following the methodology used to determine Nissan Fishhook dwell times was straightforward. In Parts 1 and 2, the desired roll rate and lateral acceleration zero crossings produced by the various handwheel inputs were easily identified. One test performed with the Ford Escape did, however, reveal what could be a significant shortcoming in Nissan's technique.

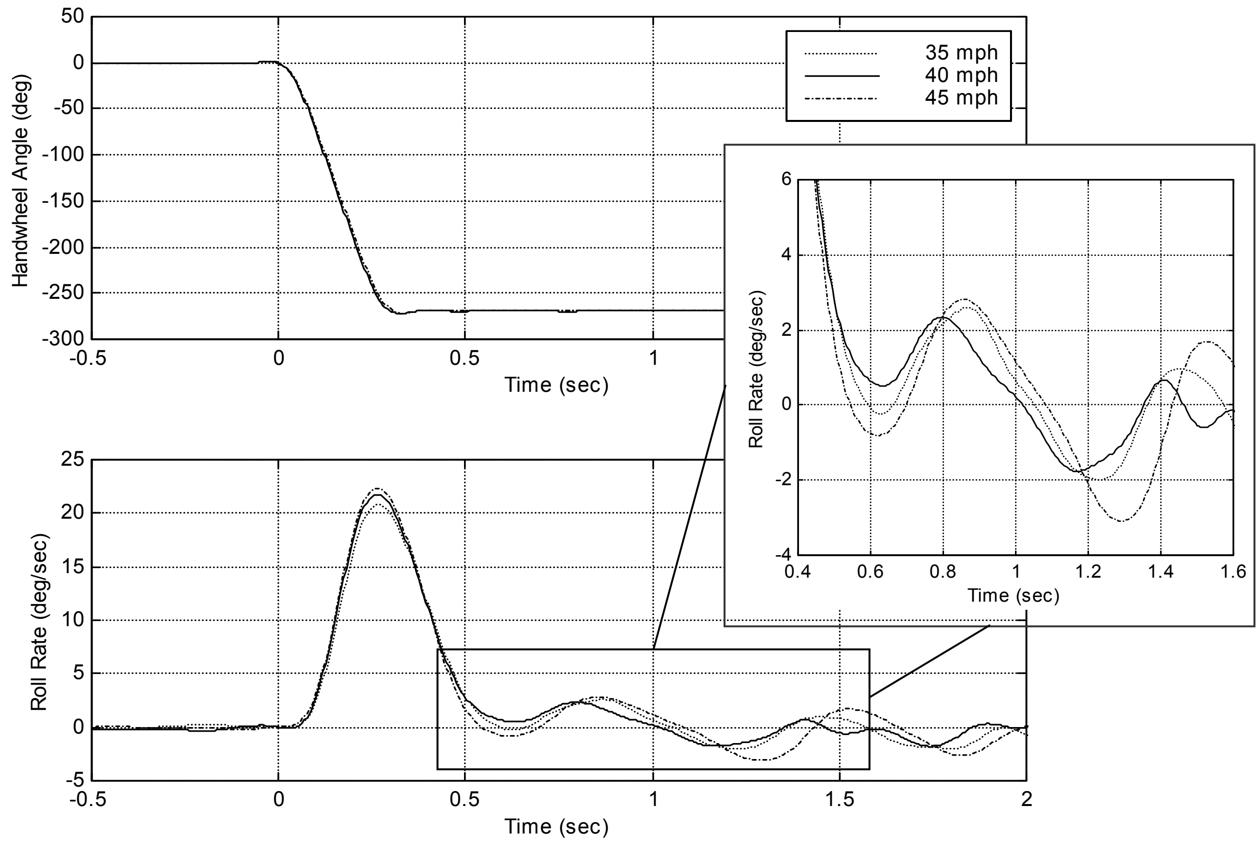

Figure 10.7. Roll rate response of the Ford Escape to the Nissan Fishhook Part 1step-steer input.

When the Ford Escape was evaluated in Part 1 at 40 mph, roll rate approached zero after completion of the step-steer, but did not pass through it until the second rebound (see Figure 10.7). As a result, the time of the third roll rate zero crossing was extended. This differs from the results produced during left steer tests performed at 35 and 45 mph, also shown in Figure 10.7.

In Part 3, the time between the third roll rate zero crossing produced in Part 1 and the first lateral acceleration zero crossing produced in Part 2 (zero dwell time fishhooks), Δ_t, was evaluated. These times are intended provide the experimenter with a logical basis for which to begin the iterative process of fishhook dwell time determination. The results of Part 3, for the Ford Escape, are provided in Table 10.2.

Table 10.2. Nissan Fishhook Summary for the Ford Escape (Parts 1 and 2).

Speed	Direction of Steer[1]	Time of Zero Crossings		Δ_t (seconds)
		3rd Roll Rate Zero Crossing (seconds)	1st Lateral Acceleration Zero Crossing (seconds)	
35	L	1.055	0.685	0.370
	R	1.000	0.680	0.320
	Average	**--**	**--**	**0.345**
	Std Dev	**--**	**--**	**0.035**
40	L	1.465	0.695	0.770
	R	1.070	0.690	0.380
	Average	**--**	**--**	**0.575**
	Std Dev	**--**	**--**	**0.276**
45	L	1.090	0.705	0.385
	R	1.055	0.695	0.360
	Average	**--**	**--**	**0.373**
	Std Dev	**--**	**--**	**0.018**
50	L	1.115	0.730	0.385
	R	1.025	0.710	0.315
	Average	**--**	**--**	**0.350**
	Std Dev	**--**	**--**	**0.049**

[1]Initial direction of steer for fishhook handwheel inputs.

When data collected during tests performed at 40 mph was considered, left and right steer Δ_t calculations (770 and 380 milliseconds) differed by 51 percent. In this case, the large difference in Δ_t values makes the use of a composite dwell time (calculated by averaging left and right steer durations for a given test speed) inappropriate, as indicated by the high standard deviation of the 40 mph composite shown in Table 10.2.

For the Ford Escape, with the exception of the left-right steer fishhook performed at 40 mph, a commanded dwell time of 300 milliseconds (the actual dwell time averaged 67 milliseconds shorter) was able to produce a first lateral acceleration zero crossing during the actual maneuver that occurred within ±50 milliseconds of the third roll rate zero crossing during a previously performed step-steer as required by Nissan's methodology. When this commanded dwell time was used during right-left fishhook testing at 40 mph, the time of the first lateral acceleration zero crossing during the fishhook and the time of the third roll rate zero crossing during the step-steer differed by 15 milliseconds. However, when left-right tests were performed with the same commanded dwell time, the difference became 400 milliseconds. However, we made a decision to use the 300 millisecond commanded dwell time anyway.

Although the left-right fishhook initiated at 40 mph was not performed in accordance with Nissan's *methodology*, the authors do not believe significantly increasing the dwell time would have been in agreement with the their intended *objective*. Like the Fishhook 1b, Nissan Fishhook steering endeavors to maximize roll rebound. As previously mentioned, all other Nissan Fishhook tests performed with the Ford Escape were successfully executed with 300 millisecond commanded dwell times (the actual range of dwell times during Nissan Fishhook testing with the Escape was 215 to 255 milliseconds). This was in good agreement with the 180 to 230 milliseconds range of dwell times that occurred during Fishhook 1b testing with the Escape. (A complete dwell time comparison for the Fishhook 1b and the Nissan Fishhook are in Chapter 15.) The dwell time of the left-right Fishhook 1b performed at 40 mph was 220 milliseconds. These data all indicate that the Escape's roll momentum is best preserved for the left-right fishhook at 40 mph with a dwell time much less than that which would have been determined form the Nissan methodology.

10.6 Nissan Fishhook Results

10.6.1 Two-Wheel Lifts

Of the three fishhooks evaluated during Phase IV testing, the Nissan Fishhook proved to be the least effective in producing two-wheel lift. Table 10.3 summarizes the two-wheel lifts for Nissan Fishhooks performed with the Chevrolet Blazer and Ford Escape. The Toyota 4Runner and Mercedes ML320 were not evaluated using the Nissan Fishhook.

Table 10.3. Nissan Fishhook Two-Wheel Lift Summary.

Vehicle	Left-Right			Right-Left		
	Two-Wheel Lift (mph)	Dwell Time (ms)		Two-Wheel Lift (mph)	Dwell Time (ms)	
		Commanded	Actual		Commanded	Actual
2001 Chevrolet Blazer	46.1	100	40	None (Max Speed = 51.4)	100	40
2001 Ford Escape	None (Max Speed = 49.4)	300	245	None (Max Speed = 50.2)	300	220

The Nissan Fishhook produced two-wheel lift for the Chevrolet Blazer when left-right steering was input. No two-wheel lift was occurred during right-left Blazer tests, or during any Ford Escape tests. This was in agreement with results produced with Fishhook 1a inputs in the Nominal Load configuration, although the two-wheel lift occurred when a lower entrance speed was used (40.2 mph). Fishhook 1b produced two-wheel lift for both directions of initial steer; left-right tests performed at 40.3 mph, and right-left tests produced at 40.1 mph both produced two-wheel lift.

10.6.2 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact were occurred during Nissan Fishhook testing, regardless of the occurrence/non-occurrence of two-wheel lift.

10.7 Nissan Fishhook Maneuver Assessment

Using the criteria presented in Chapter 2, the authors have rated the Nissan Fishhook maneuver in the following manner:

Objectivity and Repeatability = Good

The Nissan Fishhook was performed with good objectivity and repeatability. By using the programmable steering machine, handwheel inputs were precisely executed, and able to be replicated from run-to-run. Test drivers were able to achieve maneuver entrance speeds an average of ± 0.9 mph from the desired target speed.

Note that the Objectivity and Repeatability rating of the Nissan Fishhook maneuver was reduced from that assigned to Fishhook 1a. This was due to roll rate zero-crossing variability observed in response to the step steer used in Part 1 of the maneuver. The Nissan Fishhook requires accurate determination of the third roll rate zero-crossing following input of the step steer. This is because zero crossing variability directly affects what dwell time duration will ultimately satisfy

Nissan's requirements. If the third roll rate zero crossing is delayed (e.g., due to an anomalous response produced during the step-steer) an inappropriate dwell time extension will result.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data occurred during Nissan Fishhook tests were highly repeatable. That said, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, lower than that occurred at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of Nissan Fishhook maneuver.

Performability = Satisfactory

Objective and repeatable Nissan Fishhook maneuvers were easily performed with the programmable steering controller. Use of the iterative dwell time determination process allowed the timing of Nissan Fishhook handwheel inputs (the duration of the dwell time) to adapt to a given set of test conditions (e.g., maneuver entrance speed, load configuration, stability control intervention). Unlike Fishhook 1b, however, this adaptation did not occur on a test-to-test basis.

The Nissan Fishhook has a well worked out test procedure. However, this test procedure does not effectively adapt handwheel input magnitudes to the vehicle being evaluated. All vehicles subjected to Nissan's methodology use identical initial steer magnitudes. While the reversal magnitudes do change on a vehicle-to-vehicle basis, these changes only insure the commanded input does not exceed the range of handwheel angles permitted by a given vehicle's steering system. Adjustment of the steering magnitude for the characteristics of the vehicle being tested could probably be added to the current test procedure without difficulty.

The primary disadvantage of the Nissan Fishhook, compared to Fishhook 1b, is in the performability area; the steps/iterations required by Nissan's methodology requires a large number of tests to be performed. Three to four times as many tests are required for the Nissan Fishhook as are required for Fishhook 1b. To minimize the effects of tire wear on test results, numerous tire changes were required over the course of a single vehicle's evaluation. This increased the testing burden (time and cost) considerably.

The Nissan Fishhook has some performability advantages over Fishhook 1b. One advantage is that by not using roll rate feedback you avoid the occasional need for repetitions caused by anomalies in the roll rate measurement. Another advantage is that the Nissan Fishhook requires a less sophisticated steering machine, since the machine need not possess the ability to reverse direction of steer at maximum roll angle. A less sophisticated steering machine should cost less than a more advanced unit (i.e., one that permits roll rate feedback). A third advantage is the reduced real estate required for testing. The Nissan Fishhook does not require results from the Slowly Increasing Steer maneuver to define its handwheel inputs (the relationship of handwheel angle to lateral acceleration is not used). As such, the Nissan Fishhook may be performed at facilities unable to support use of the Slowly Increasing Steer / Fishhook 1b maneuver combination.

The Nissan Fishhook uses a very high steering wheel angle rate (1,080 degrees per second). Our programmable steering controller has some difficulty with such a high rate. Changing to the lower steering wheel angle rate (720 degrees per second) used for the Fixed Timing and Roll Rate Feedback Fishhooks would probably only minimally affect maneuver results. Reduction of the magnitude of the countersteer to the amount used for the Fixed Timing and Roll Rate Feedback Fishhooks should slightly increase maneuver severity. Our experience has been that the large countersteer used by the Nissan Fishhook slows the vehicle.

Discriminatory Capability = Excellent

The Nissan Fishhook was an excellent maneuver for measuring the rollover resistance of different vehicles. The dynamic rollover propensity of only the Chevrolet Blazer and Ford Escape was assessed using the Nissan Fishhook, and all tests were performed in the Nominal Load configuration. Two-wheel lift was produced during tests performed with the Chevrolet Blazer.

The results obtained with Nissan's methodology were in good agreement with those produced during Fishhook 1a and 1b tests. That said, the entrance speed of the Nissan Fishhook test for which two-wheel lift occurred was approximately 6 mph higher than that of either NHTSA Fishhook. This implies that the two NHTSA fishhooks offer better discriminatory capability than does the Nissan Fishhook.

Although only two Phase IV vehicles were evaluated with the Nissan Fishhook, it appears the maneuver, is capable of doing an excellent job of discriminating between different levels of untripped rollover resistance for typical, current generation, sport utility vehicles. However like Fishhook 1a and 1b, it is unlikely the maneuver will be capable of such discrimination for the entire light vehicle fleet. The authors do not anticipate many two-wheel lifts will occur during testing of vehicles that have a Static Stability Factors of 1.13 or greater (e.g., vehicles that earn three or more stars under NHTSA's current rollover rating program). That said, results produced with the Nissan Fishhook relate well with results produced with Fishhook 1a and 1b, two maneuvers known to NHTSA to cause two-wheel lifts for vehicles in the above 1.13 SSF range (e.g., for the Mercedes ML320). Therefore, it seems the Nissan Fishhook maneuver does as good a job of discriminating throughout the entire fleet of vehicles as will any other on-road, untripped Rollover Resistance maneuver if the occurrence of two-wheel lift is used as a criterion.

Appearance of Reality = Excellent

The handwheel inputs defining any fishhook maneuver approximate the steering a driver might use in an effort to regain lane position on a two-lane road after dropping the two passenger-side wheels off onto the shoulder.

11.0 FORD PATH-CORRECTED LIMIT LANE CHANGE (PCL LC)

The Ford Motor Company's Path-Corrected Limit Lane Change (PCL LC) was one of four closed-loop Rollover Resistance maneuvers used in Phase IV[1]. Unlike the closed-loop maneuver (Fishhook 1b) discussed earlier in this report, this was a driver-based maneuver, i.e., the test driver closed the steering control loop.

Ford has proposed this test protocol as a dynamic rollover resistance rating procedure that meets the requirements of the TREAD Act, and stated that, in Ford's opinion, its output is an improvement over NHTSA's Static Stability Factor (SSF) metric. The procedure normalizes vehicles trajectories so as to reduce/remove the effects of driver-to-driver differences or test site differences.

The precise details of the PCL LC test procedure are proprietary to Ford Motor Company. Ford has allowed NHTSA to evaluate the PCL LC technique under a confidentiality agreement. Therefore, the descriptions of the PCL LC test procedure and data-normalization technique contained in this report are necessarily vague. Ford and NHTSA performed the work described in this chapter as collaborative research. NHTSA expects Ford would make the details of the procedure public if it [NHTSA] proposed the test protocol to be the dynamic rollover resistance test mandated by the TREAD Act.

This chapter is comprised of seven sections. Section 11.1 describes the three primary elements of the PCL LC procedure. Sections 11.2 and 11.3 discuss steering input and vehicle speed repeatability. Section 11.4 discusses output repeatability. Section 11.5 presents test results. Section 11.6 discusses Ford's continuing development of this procedure. Section 11.7 provides an assessment of the procedure and concluding remarks.

11.1 PCL LC Maneuver Description

The PCL LC was comprised of three primary elements: driver-based tests performed on a test track using a suite of double lane change courses, a data-normalizing technique used to reduce or eliminate the effects of test variability, and a rollover resistance metric based on dynamic weight transfer.

11.1.1 Test Track Double Lane Change Courses

To begin each test during the testing phase of the PCL LC procedure, the vehicle was driven in a straight line at a constant speed of 45 mph. At the course entrance, the driver released the throttle and steered the vehicle through the course apertures.

To provide the data required by the PCL LC normalizing technique, a suite of courses were used. The use of multiple courses ensured that the vehicle was exercised through a range of frequencies and amplitudes. Three markers placed on the pavement delimited the path's lane change apertures with the middle marker representing an avoidance obstacle. Varying the position of the markers laterally and longitudinally produced an array of responses. Figure 11.1

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[1] These maneuvers include the Fishhook 1b, the Path Corrected Limit Lane Change, the ISO 3888 Part 2 Double Lane Change, and the Consumers Union Short Course Double Lane Change.

shows the suite of course layouts specified by Ford. Tests are run with initial steering to the left and repeated with initial steering to the right.

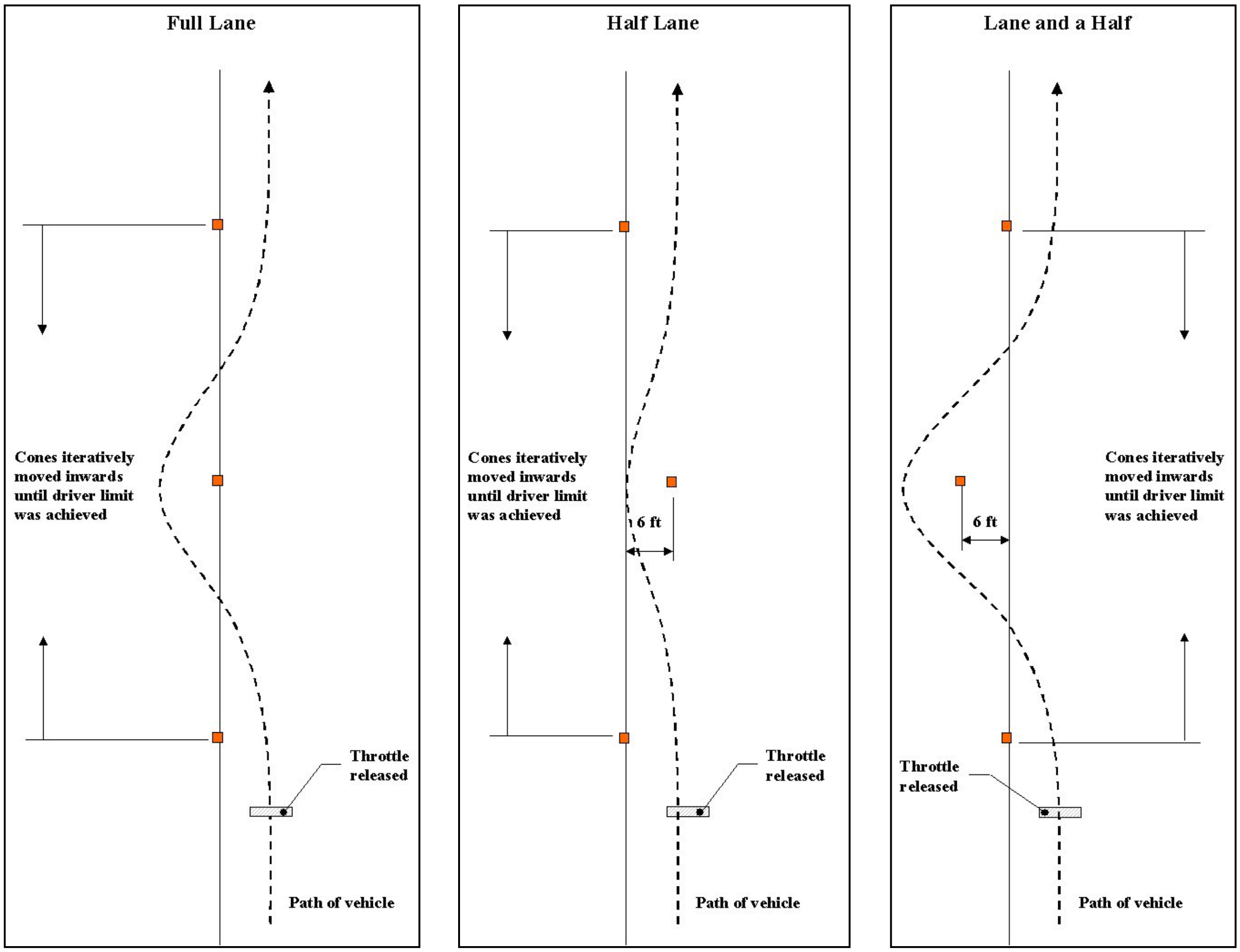

Figure 11.1. Suite of paths used during the test track phase of the PCL LC procedure (not to scale) Maneuvers were performed with left and right initial directions of steer.

Testing began with the top and bottom markers in each of the courses shown in Figure 11.1 far (in the longitudinal direction) from the central marker, making it easy for drivers to drive through each course without hitting cones. A number of iterations were then performed. The goal of the iterations was to exercise the vehicle at a number of fundamental steering frequencies. For each iteration, the top and bottom markers in each course were moved towards the central marker. The vehicle was then driven through the course. Note that the lateral position of the markers did not vary between iterations for a given course. The iterations continued until, in the judgment of the person running the testing, the maximum capabilities of the driver/vehicle were required to negotiate the course. Several, repeated, runs were made using the most severe geometry for each test course.

Unlike the ISO 3888, Part 2 and the Consumers Union Short Course Double Lane Changes, data from both "clean" and "not clean" PCL LC runs was retained for processing[2]. Ford checked during data processing to ensure that test drivers input a sufficient range of steering frequencies and magnitudes to permit the rollover resistance metrics to be calculated.

As discussed above, the PCL LC testing was performed as collaborative research between Ford Motor Company and NHTSA. PCL LC testing used the same test vehicles as did the other Phase IV testing. All vehicles were tested only in their Nominal Load configuration. Ford provided on vehicle instrumentation and data acquisition; the instrumentation described in Chapter 4 was not used for this testing. Ford personnel performed the bulk of this testing; NHTSA personnel observed all of the testing. A Ford driver tested each vehicle. One vehicle was also tested using NHTSA drivers.

11.1.2 PCL LC Normalizing Technique

The PCL LC methodology required that test vehicles be "driven" through a suite of standardized paths. Note that these paths are *derived* with test data, and are not necessarily the same as the courses presented in Figure 11.1. This process includes an analysis technique that ensures all vehicles experience the same magnitude of lateral acceleration when "driven" through the standardized paths. Ford has suggested 0.7 g is an appropriate target for lateral acceleration, as this level should attainable by most vehicles on most test surfaces. By normalizing the lateral acceleration of the vehicles as they are driven through the standardized paths, Ford endeavors to negate the effects of driver and surface variability on the test results.

The PCL LC methodology "drives" the test vehicles through a suite of standardized paths by use of mathematical post-processing. The post-processing procedure operates on the test data, as stated on Page 4 of [20], "to normalize the varying results of physical tests to a uniformly based metric." The results predict how various vehicles would perform had they followed identical, standard, paths.

Ford states on Page 5 of [20], "Post-test computer aided normalizing techniques have been sufficiently developed that we have high confidence in their applicability to this issue. The PCL LC technique uses physical test data to define a vehicle-specific transfer function. These functions are then used to normalize metric values, such as dynamic weight transfer, to a specific vehicle path common to all vehicles evaluated. The data suggests that use of these normalizing techniques eliminates concerns that may arise because of test driver variability and by subjecting the vehicles to the same path, help to eliminate track surface variability, thus providing the only dynamic test method and metric unaffected by these sources of variability. We believe this is a technically sound method to achieve reliable, repeatable and objectively stated results that will improve upon SSF based star ratings."

Ford allowed NHTSA to evaluate the PCL LC normalizing technique under a confidentiality agreement. Thus, specific details of the procedure are not available for this report. Were NHTSA to propose that Ford's PCL LC normalizing technique be used as part of the best

[2] A "clean" run was one in which none of the cones used to delineate a course were either struck or bypassed.

dynamic rollover resistance test for meeting the requirements of the TREAD Act, then NHTSA expects that Ford would make the PCL LC procedure generally available.

11.1.3 Dynamic Weight Transfer Metric

Ford's proposed rollover resistance metric is based on dynamic lateral weight transfer. Ford defines dynamic weight transfer on Page 1 of [21] as the "percentage of weight that is removed from a vehicle's two inside tires during a severe lane change." Using data normalized in the manner described in the previous section, the Dynamic Weight Transfer Metric (DWTM) is defined as the maximum percent of dynamic weight transfer averaged over a minimum specific time. Ford recommends a minimum specific time of 400 milliseconds.

Ford believes that DWTM shows differences in performance between vehicles and therefore provides a way to rank them. Larger DWTM values indicate that a vehicle has a greater propensity to rollover (less rollover resistance). Ford states that DWTM is more useful than SSF as an indicator of rollover resistance because it is affected by more vehicle properties than is SSF. In addition to the properties that determine SSF (i.e., center of gravity height and track width) DWTM can be affected by: suspension compliance, kinematics, and roll stiffness; tire compliance and stiffness; roll inertia and damping; and movement of the center of gravity during roll.

DWTM is described mathematically.[3]

$$\mathrm{DWTM} = \max\left(\mathrm{DWT}_{\mathrm{Left}}, \mathrm{DWT}_{\mathrm{Right}}\right)$$

$$\mathrm{DWT}_{\mathrm{Left}} = 100\left(1 - \frac{\min(\mathrm{LeftFz})}{\mathrm{LeftFz}_{\mathrm{Static}}}\right)$$

$$\mathrm{DWT}_{\mathrm{Right}} = 100\left(1 - \frac{\min(\mathrm{RightFz})}{\mathrm{RightFz}_{\mathrm{Static}}}\right)$$

$$\mathrm{LeftFz} = \mathrm{LFFz} + \mathrm{LRFz}$$

$$\mathrm{RightFz} = \mathrm{RFFz} + \mathrm{RRFz}$$

$$\mathrm{LeftFz}_{\mathrm{Static}} = \mathrm{LFFz}_{\mathrm{Static}} + \mathrm{LRFz}_{\mathrm{Static}}$$

$$\mathrm{RightFz}_{\mathrm{Static}} = \mathrm{RFFz}_{\mathrm{Static}} + \mathrm{RRFz}_{\mathrm{Static}}$$

Where,

LFFz, RFFz, LRFz, and RRFz ≡ 400 ms moving average of vertical force on left front, right front, left rear, and right rear tires respectively

$\mathrm{LFFz}_{\mathrm{Static}}$, $\mathrm{RFFz}_{\mathrm{Static}}$, $\mathrm{LRFz}_{\mathrm{Static}}$, and $\mathrm{RRFz}_{\mathrm{Static}}$ ≡ static weight on the left front, right front, left rear, and right rear tires respectively

[3] Copied from Page 3 of Appendix III of [20].

To determine DWTM from PCL LC testing, Ford collected or calculated the following test data:

- Lateral and longitudinal acceleration
- Yaw and roll rate
- Steering wheel angle
- Longitudinal and lateral speed
- Roll angle
- Vertical tire load (from measured tire deflection)

The vehicle roll angle was calculated from vehicle side-to-side height sensor data (conceptually equivalent to the method used by NHTSA). Vertical tire load was determined with an analysis technique that combined laser height sensor data and previously measured tire data. Using two laser height sensors (suspended from a spindle attached to each wheel), dynamic tire compression and camber angle were measured. These data were correlated to tire load measurements performed on flat surface tire dynamics machine as a function of tire compression and camber angle.

To provide the data required by the PCL LC normalizing technique, Ford developed procedures that used modular test equipment (see Figure 11.2). The same equipment can be installed on many light vehicles, and flat surface tire dynamics machine measurements can be performed on a wide variety of tires. As an alternative to Ford's procedure, wheel load transducers could be used to directly measure tire load. However, the cost of adapting wheel load transducers to a large number of vehicles is very high.

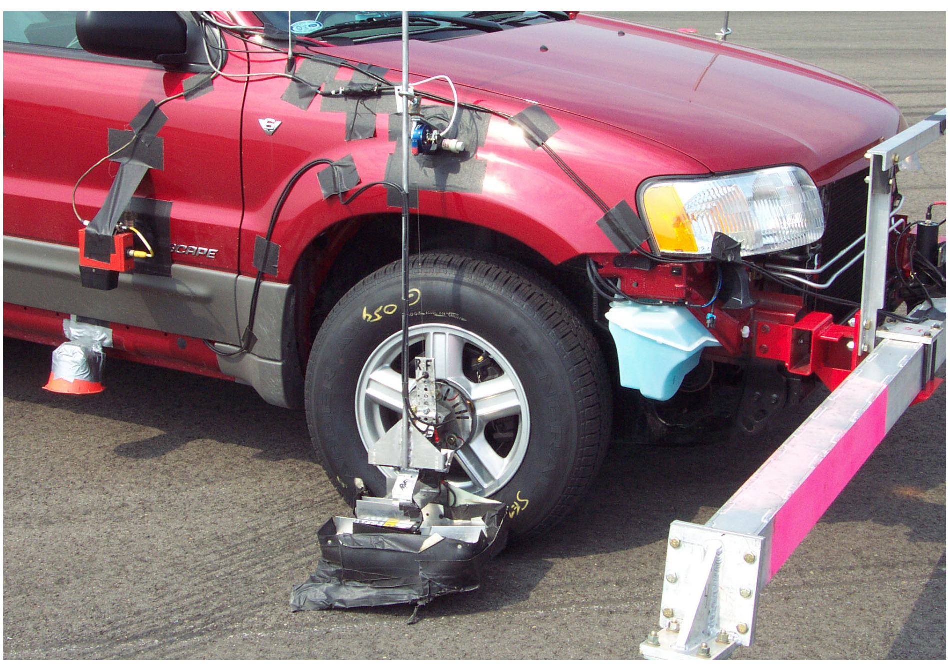

Figure 11.2. Ford test equipment used to measure data for the calculation of the DWTM.

Ford allowed NHTSA to evaluate the PCL LC DWTM under a confidentiality agreement. Thus, specific details of the procedure used to determine DWTM are not available for this report. Were NHTSA to propose that Ford's PCL LC normalizing technique be used as part of the best dynamic rollover resistance test for meeting the requirements of the TREAD Act, then NHTSA expects that Ford would make the PCL LC procedure generally available.

11.2 PCL LC Steering Input Repeatability

Unlike the Phase IV test maneuvers that required use of the steering, the PCL LC procedure did not specify steering inputs. *Drivers* steered the vehicles through Ford's suite of course layouts. Since Ford states that steering/path repeatability is not important when using their procedure since the PCL LC normalizing technique assures "that all vehicles follow the same path,[4]" the assessment of steering input repeatability used for other maneuvers was not appropriate for the PCL LC.

11.3 PCL LC Vehicle Speed Repeatability

Ford's test procedure required vehicles to enter the courses with a nominal entrance speed of 45 mph. Given the course layouts, use of a 45 mph entrance speed ensured that a lateral acceleration of at least 0.7 g was attained. Note that entrance speed variability was not important provided the data recorded during the testing of a vehicle produced sufficient information for the determination of the standardized paths. During the test track phase of the PCL LC procedure, data was analyzed as the testing progressed. Testing continued until sufficient data was produced.

11.4 PCL LC Output Repeatability

The severity metric of the Ford PCL LC procedure, DWTM, was produced from the outputs of several data channels collected during several test series. Thus, there is little basis for comparison of the outputs between individual test runs.

The most appropriate output comparison is therefore one based on results from multiple drivers. To support this comparison, three drivers were used in the evaluation of the Mercedes ML320 with disabled stability control. Since Ford's PCL LC normalizing technique endeavors to remove driver effects, the DWTM for a particular vehicle should be independent of what driver performs the test. Results from this analysis are presented in Section 11.5.4. Due to the time limitations, only one vehicle was testing with multiple drivers during the NHTSA/Ford collaborative testing effort.

11.5 PCL LC Results

The four Phase IV test vehicles were used to evaluate the PCL LC procedure. The Toyota 4Runner and Mercedes ML320 were tested with their stability control systems enabled and disabled. All vehicles were tested in their Nominal Load configuration.

[4] Copied from Page 3 of [20]

The PCL LC normalizing technique was used to determine the DWTM of each vehicle in four specific paths: 12 foot lateral movement with initial turn to the right; 12 foot lateral movement with initial turn to the left; 18 foot lateral movement with initial turn to the right; and 18 foot lateral movement with initial turn to the left.

All PCL LC data was processed and analyzed by Ford. Additionally, Ford determined the DWTM of test vehicle. Those results, along with NHTSA's observations, are discussed in the following sections.

11.5.1 Dynamic Weight Transfer Metric

Dynamic Weight Transfer Metric (DWTM) results for each of the Phase IV vehicles are presented in Figure 11.3. The values presented in the graph have been normalized and are the overall maximum dynamic weight transfer metric for each vehicle at 0.7 g for the four paths listed above. Ford states that reporting the DWTM is appropriate because no single path has greater importance than any other does. With the exception of the Mercedes ML320 with disabled stability control, all test track data used to compute the DWTMs reported in Figure 11.3 were collected during tests performed with the same driver. The DWTM of the ML320 with disabled stability control reported in Figure 11.3 was the average maximum DWTM for three drivers.

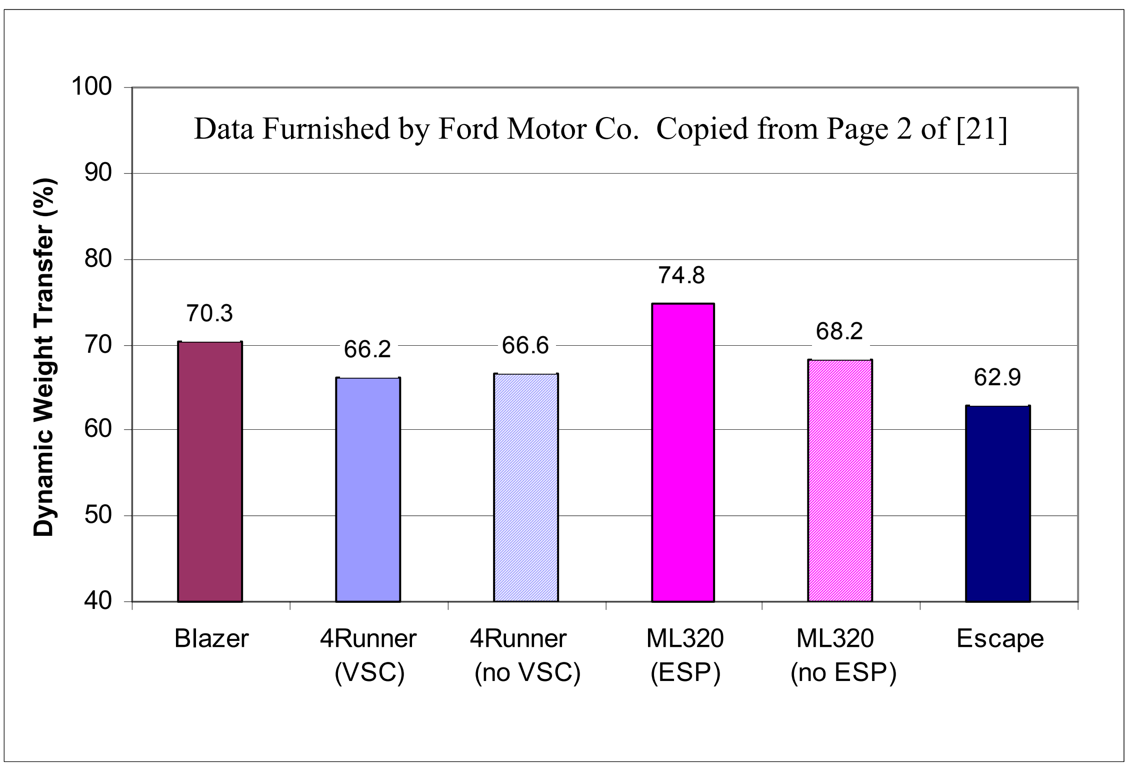

Figure 11.3. DWTM summary. The Static Stability Factor of the test vehicles increases from left to right.

The standard deviation of DWTM calculated from all tests conducted by Ford over several months for a variety of vehicles with various test drivers is 4.4 percent.[5] Ford compared this standard deviation to the DWTM range resulting from the six Phase IV vehicle configurations, and states that this comparison confirms the ability of their test protocol to show differences between the rollover resistance performances of various vehicle models and configurations.

11.5.2 Surface Independence

All tests performed during the test track phase of the PCL LC procedure were made on the same surface (the TRC VDA). However, Ford states that by ensuring that all vehicles experience the same lateral acceleration, the effects of surface variability on test results are negated. Ford reported an analysis of results from in-house evaluations of the PCL LC procedure showed a statistically insignificant difference in mean values of DWTM from tests of the same vehicle performed on two test surfaces with dissimilar friction coefficients.

11.5.3 Driver Independence

To gauge the ability of the procedure to provide driver-independent results, one Ford and two NHTSA test drivers drove the Mercedes ML320 with disabled stability control through the test track phase of the PCL LC procedure. Ford's test driver had ample experience with the procedure; the NHTSA drivers had experience with other lane change tests but not with Ford's suite of courses.

The results are shown in Figure 11.4. Values presented in the graph have been normalized and are the overall maximum dynamic weight transfer metric for each vehicle at 0.7 g for the four paths listed above. The left turn results for Driver A are not included because of a partial instrumentation failure during those runs. Ford states that these results confirm driver independence since the range of DWTM for any one path was smaller than the previously indicated overall standard deviation for the procedure of 4.4 percent.

[5] Refer to the "Objectivity and Repeatability" discussion in Section 11.7

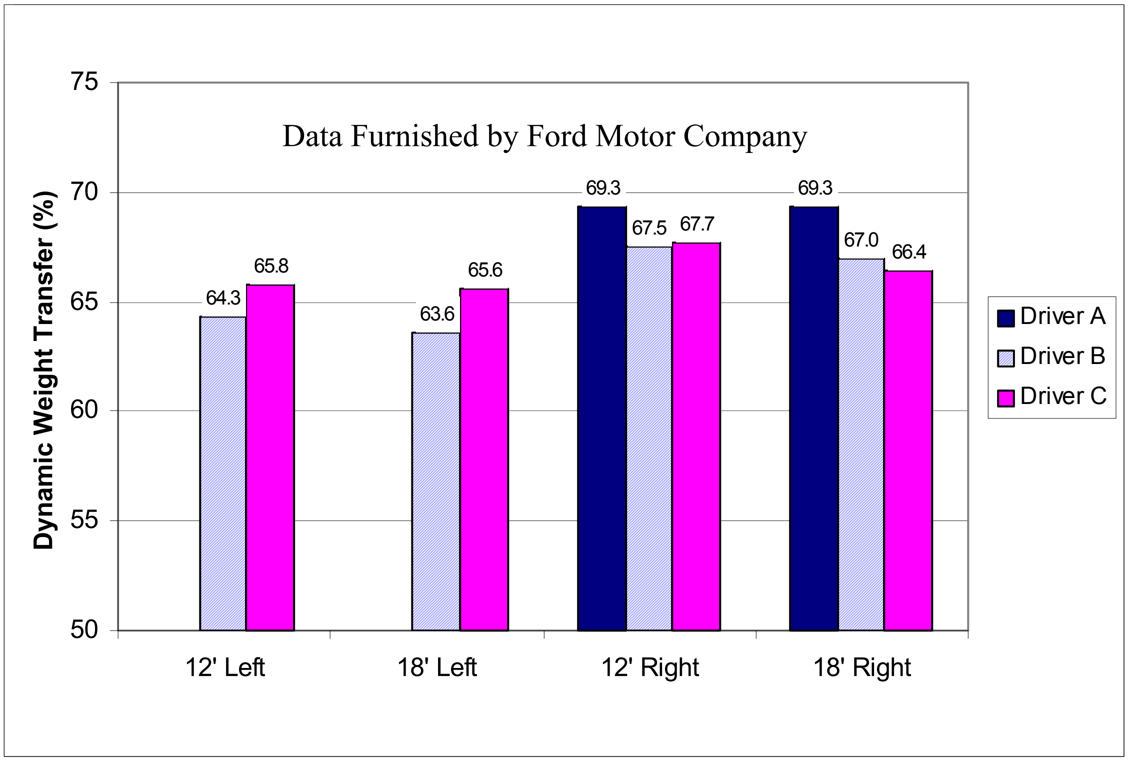

Figure 11.4. DWTM summary for tests performed by three drivers using the Mercedes ML320 with disabled stability control. Data copied from Page 5 of Appendix B of [21]

11.5.4 Two-Wheel Lift

The test track phase of the PCL LC procedure did not produce any two-wheel lift for any Phase IV test vehicle. Note that the PCL LC procedure was designed to normalize lateral acceleration to 0.7 g, a magnitude below the maximum lateral acceleration observed during Slowly Increasing Steer or Slowly Increasing Speed testing.

11.5.5 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact were observed during the test track phase of the PCL LC procedure.

11.6 Further Development of the Test Procedure by Ford

Ford presented the PCL LC procedure to NHTSA as an interim recommendation. They acknowledge that it does not consider the effects of all systems that may enhance a vehicle's crash avoidance capabilities, such as electronic stability control, and that it does not maintain surface independence for all parameters.

Since presenting the PCL LC procedure to NHTSA, Ford has developed a GPS-guided steering robot that provides closed-loop position control for test vehicles. The steering robot eliminates driver variability concerns, thereby eliminating the need for the PCL LC normalizing technique. The DWTM metric has been retained. The steering robot and GPS system provide closed-loop vehicle guidance through a suite of eight double lane change paths (four tests are performed with an initial left steer, four with an initial right steer). A local differential GPS antenna enables a claimed position accuracy of two centimeters. The combined system steers a vehicle to the entrance of a path from any point on a test surface and aligns the vehicle with the centerline of the path. The test driver controls the throttle.

Ford typically ballasts vehicles to achieve GVWR and rear GAWR simultaneously during their in-house tests (similar to the Modified Handling configuration used for the Chevrolet Blazer and Toyota 4Runner in Phase IV). Water dummies weighing 150 lb. occupy every seat. A load box is placed behind the rear seats, or in the trunk or cargo bed, and weighted with lead shot. The position and weight of the box are adjusted to achieve the specified ballast. Ford states that, in general, the water dummies raise the vertical CG while the load box lowers it.

11.7 PCL LC Maneuver Assessment

Using the evaluation factors presented in Chapter 2, the authors have rated the NHTSA J-Turn maneuver as follows:

Objectivity and Repeatability = Bad

The Path-Corrected Limit Lane Change (PCL LC) procedure consisted of a series of closed-loop (test driver generated steering inputs) double lane changes. Data collected during these double lane changes is then processed "to assure that all vehicles follow the same path and are subject to the same acceleration demands.[6]" Ford has recommended the calculation of a Dynamic Weight Transfer Metric (DWTM) at 0.7 g lateral acceleration as the appropriate rollover resistance metric for this maneuver. "Because different vehicle designs will react differently to forces of varying magnitude and time duration, a suite of various paths should be analyzed in determining an overall dynamic weight transfer metric (DWTM), based on values of maximum weight transfer.[7]"

Ford has performed a substantial amount of PCL LC testing. While NHTSA does not have access to this data, Ford has summarized this data as follows: "Ford's overall standard deviation for the DWT metric is 4.4 [percent] from multiple tests made on a variety of vehicles with a variety of drivers, over a time span of several months and using a new set of tires fitted for each test.[8]" To understand the meaning of this standard deviation, we need to know the expected range of the dynamic weight transfer metric.

The most basic way to estimate this range is to approximate the vehicle as a rigid block in a steady state curve at 0.7g lateral acceleration. Using this approximation, the expected range of DWTM values is from 46.7 percent (corresponding to a vehicle with a static stability factor of 1.50) to 70.0 percent (corresponding to a static stability factor of 1.00).

[6] Copied from Page 3 of [20]
[7] Copied from Page 1 of [20]
[8] Copied from Page 2 of [21]

Real vehicles, of course, are not rigid bodies. They have compliant suspensions and tires. This increases the DWTM values from those of rigid vehicles. Based on NHTSA's Tilt Table data and assumptions about the difference between tilt table and flat track testing, we estimate an addition of about 4 to 8 percent to the rigid body DWTM calculations as a result of quasi-static body roll at 0.7 g. Applying the average addition of 6 percent DWTM makes the expected range of DWTM approximately 53 to 76 percent. Therefore, Ford's standard deviation of 4.4 percent for DWTM is 19 percent of the entire expected range of DWTM values.

Another way to understand the meaning of this standard deviation is to analyze the values of DWTM that were measured by Ford and NHTSA during joint testing of the rollover test vehicles. Table 11.1 lists these values, along with the number of observations that these values are based on, the calculated dynamic weight transfer at 0.7 g lateral acceleration based on a rigid body model, and the difference between these two dynamic weight transfer values.

Table 11.1. Measured and Calculated Dynamic Weight Transfers[9].
(The Static Stability Factors of the Test Vehicles increase from left to right).

Description	2001 Chevrolet Blazer	2001 Toyota 4Runner (with VSC)	2001 Toyota 4Runner (no VSC)	1999 Mercedes ML320 (with ESP)	1999 Mercedes ML320 (no ESP)	2001 Ford Escape
DWTM Measured with PCLLC	70.3%	66.2%	66.6%	74.8%	68.2%	62.9%
Number of Observations	4	4	4	4	10	4
Calculated Weight Transfer	67.3%	63.1%	63.1%	60.9%	60.9%	57.9%
Difference	3.0%	3.1%	3.5%	13.9%	7.3%	5.0%

Consider the Chevrolet Blazer and the Ford Escape. The Blazer receives one star; one of the lower ratings for sport utility vehicles from NHTSA's current rollover rating system (which is based on Static Stability Factor). The Ford Escape has an SSF at the high end of the three star range; one of the higher ratings for sport utility vehicles. Most sport utility vehicles have Static Stability Factors between these two vehicles.

Now look at the DWTM values for these vehicles as measured using the PCL LC procedure. For the Chevrolet Blazer the measured DWTM value is 70.3. However, based on Ford's standard deviation and the number of samples, we have 95 percent confidence that the DWTM for this vehicle is between 66.0 and 74.6. Similarly, for the Ford Escape we have 95 percent confidence

[9] Values taken from Page 2 of [21]

that the DWTM is between 58.6 and 67.2. Note that these ranges overlap! However, the difference between these two vehicles DWTM values is statistically significant (although just barely having a t-value of 2.38 versus the critical t-value of 2.37).

A measurement standard deviation for which the difference between a sport utility vehicle with high rollover resistance and one with low rollover resistance is only marginally statistically significant is too large for generating vehicle ratings.

Table 11.1 shows another problem with the measured DWTM values. When we estimated the expected range of DWTM as 53 percent to 76 over the entire range of vehicles from SUVs to sport sedans, we considered only the quasi-static load transfer due to the vehicle's rigid body geometry and to its steady state body roll. We neglected the dynamic weight transfer that occurs as a result of body roll acceleration in an abrupt maneuver. However, when the calculated steady state, rigid body weight transfer in Table 1 is subtracted from the measured DWTM, the difference is no more than that expected for the steady state body roll in all but one case. It would appear that the Dynamic Weight Transfer Metric produced by PCL LC generally measures quasi-static rather than dynamic weight transfer.

The exception is the DWTM measurement for the Mercedes ML320 with yaw stability control enabled. While the DTWM for this vehicle with yaw stability control disabled is no more than the expected quasi-static load transfer, the DTWM increases by 6.6 percent when the yaw stability control is enabled. The difference between these two values is statistically significant and would seem to represent a dynamic weight transfer component missing in the other PCLLC results in Table 11.1. However, it is hard to understand why stability control should lower the rollover resistance of this vehicle. Fishhook testing indicates just the opposite; that yaw stability control increases the rollover resistance of this vehicle. Therefore, we believe that the measured DWTM value for the Mercedes ML320 with yaw stability control enabled is incorrect.

In conclusion, the objectivity and repeatability of the Path Corrected Limit Lane Change has not yet attained an acceptable level for rating the rollover resistance of vehicles. While future improvements to the objectivity and repeatability of this maneuver can probably be made, NHTSA's Congressionally-mandated deadline under the TREAD Act forces NHTSA to look at what was available during the summer of 2001 and not at possible future enhancements.

Performability = Satisfactory

The procedure for performing this test track phase of the PCL LC procedure was straightforward. However, substantial additional instrumentation, over and above that required to perform a Fishhook maneuver, were required. Tire characterization tests performed on a flat surface tire dynamics machine were necessary. The costs and additional testing time associated with this equipment are expected to exceed the costs and additional testing time saved by not having to use a programmable steering controller.

Since Ford processed the data collected during the NHTSA/Ford cooperative testing effort, the authors are unable to say how difficult the data processing was to perform. However, with experience and the correct software it is expected to approximately equal the effort required to process data from a Fishhook or J-Turn test. There may be issues in making Ford's data processing software publicly available.

Due to the use of a suite of paths for calculating DWTM values, the PCL LC procedure should adequately adapt to differing vehicle characteristics.

We have concerns about determining dynamic weight transfer as an average value over a 400-millisecond window. The use of this broad a window may filter out dynamic effects that may be important in actual vehicle rollovers.

As discussed above, further development of this test procedure to improve measurement repeatability is required.

Discriminatory Capability = Good

No two-wheel lift was detected for any of the Phase IV vehicles during the test track phase of the PCL LC procedure. Unlike the J-Turn and Fishhook maneuvers, the occurrence/non-occurrence of two-wheel lift cannot be used as measure of vehicle performance for this maneuver. The DWTM measured in PCL LC testing produces a continuous measure of rollover resistance that, like SSF, that allows discrimination even among vehicles that are not susceptible to on-road untripped rollover.

Ford recommends the calculation of a Dynamic Weight Transfer Metric (DWTM) at 0.7 g lateral acceleration as a measure of vehicle performance for this maneuver. Data collected during testing was processed to remove driver effects by having all vehicles always follow the same standardized paths and be subjected to the same lateral acceleration demands. "Because different vehicle designs will react differently to forces of varying magnitude and time duration, a suite of various paths should be analyzed in determining an overall dynamic weight transfer metric (DWTM), based on values of maximum weight transfer.[10]" Ford's reasons for recommending DWTM are as follows:

"For a given velocity change, various vehicle related factors determine the magnitude of dynamic weight transfer for events that can lead to both tripped or un-tripped rollover. Obviously, the higher the center-of-gravity, the greater the transfer for a given travel velocity change. Similarly, the smaller the track width, the greater the transfer. As is well known, many factors other than these two affect dynamic weight transfer and it is because of this that SSF is a narrow and inadequate concept. For example, if deflections occur in suspensions, tires, or other parts that control overall body movements such as active stabilizer bars or electronically controlled shock absorbers, when dynamic forces are applied, the magnitude of the dynamic weight transfer will also change. Inertial values, yaw plane motions, vertical motions and pitch plane motions that arise because of a vehicle's design details or features can affect force and moment balances and can change vehicle configurations to affect the magnitude of the dynamic weight transfer. It is a directionally correct proposition that the greater the magnitude of the dynamic weight transfer in a given high severity event, the less margin, reserve, or resistance remains to a rollover occurring. Based on these principles, Ford believes that dynamic weight

[10] Copied from Page 1 of Appendix III of [20]

transfer is a metric of value in a dynamic test." "Our preliminary work has confirmed that this metric will discriminate among specific vehicles within a class and between classes of vehicles. We submit that DWTM is a more reliable metric than SSF alone.[11]"

"Our preliminary work suggests that vehicles within a given class are likely to have dynamic weight transfer values in an extreme double lane change maneuver that will allow the values to be used as a surrogate for vehicle type or mission. Therefore the proposed DWTM can help enable consumers to make informed choices about the tradeoffs that arise because of a vehicle's functional attributes including high ground clearance, cargo space, occupant carrying capacity and track width as they may affect rollover resistance. Use of DWTM can also highlight the effect of dynamic vehicle characteristics and features ignored by simple static measures such as SSF. DWTM provides additional choices and direction to vehicle designers that cannot be provided by SSF based information or regulation because SSF values are driven principally by vehicle mission and geometry. In addition, our preliminary development of DWTM has shown it may also be able to distinguish among the vehicles within one vehicle class, such as compacts SUV's, which SSF based consumer ratings alone cannot provide. For all these reasons, Ford currently recommends rollover resistance consumer information with the proposed dynamic weight transfer metric averaged over a specified time interval, measured in a path specified double lane change and using normalizing techniques to help achieve a vehicle DWTM that is independent of driver and surface variability.[12]"

DWTM has the theoretical advantage over SSF of including load transfer due to quasi-static body roll and true dynamic load transfer due to body roll accelerations, but its measurement by the PCLLC method seems to be lacking the dynamic load transfer component. The PCLLC test also is not able to test for the effect of yaw stability control. In its comment to the docket of the last notice, [20], Ford suggested that the same 0.7g lane change maneuvers and DTWM could be implemented directly with an advanced path following robot rather than with the PCLLC method, but it cautioned that the test would not evaluate the effect of yaw stability control. In light of this comment, it is not surprising that the PCLLC test measured no effect of yaw stability control of Toyota 4Runner, but it remains troubling that it measured a significant loss of rollover resistance for yaw stability control of the Mercedes ML320 contrary to its effect measured in other rollover maneuver tests.

NHTSA is also concerned about not exercising vehicles to the limits of their performance. By not taking vehicles to their limits, some important limit performance problems could be overlooked.

Appearance of Reality = Excellent

In general, double lane change maneuvers have an excellent appearance of reality. The handwheel inputs used by the drivers during PCL LC testing emulate the steering a driver might use in an emergency obstacle avoidance maneuver performed on a two-lane road. While the Path Corrected Limit Lane Change trajectories are idealized, rather than actual, this distinction would likely not be noticed by consumers.

[11] Copied from Pages 5 and 6 of [20]
[12] Copied from Pages 6 and 7 of [20]

12.0 CONSUMERS UNION SHORT COURSE DOUBLE LANE CHANGE

The Consumers Union Short Course Double Lane Change (CUSC) was one of four closed-loop Rollover Resistance maneuvers used in Phase IV[1]. Unlike the Fishhook 1b closed-loop maneuver discussed earlier in this report, this was a driver-based maneuver, i.e., the test driver closed the steering control loop. Since test driver generated steering inputs were used, three drivers were used for the evaluation of each vehicle. This allowed for the determination of the effects of driver variability. The programmable steering machine was not used to generate steering inputs for any CUSC tests.

This chapter is comprised of seven sections. Section 12.1 briefly introduces the maneuver with background information. Section 12.2 describes the maneuver and how it was executed. Sections 12.3 and 12.4 discuss the steering and vehicle speed input repeatability, respectively. Section 12.5 discusses output repeatability. Section 12.6 presents test results. Section 12.7 provides a maneuver assessment and concluding remarks.

12.1 Consumers Union Short Course Background Information

The CUSC was developed to observe the way vehicles respond to handwheel steering inputs drivers might use in an emergency situation. Consumers Union has stated that the goal of this maneuver is to study the emergency handling of vehicles, not necessarily to determine their rollover resistance. The CUSC scenario is comprised of a sudden, crash avoidance, steering input to the left and a rapid return to the original [right-hand] lane. The course is delineated with pylons.

The CUSC is an approximation of the path used by a Consumer Reports staff member during a test producing substantial two-wheel lift with a Suzuki Samurai. Since its inception, the CUSC has produced substantial two-wheel lift during evaluations of the 1988 Suzuki Samurai, 1996 Isuzu Trooper, and 2001 Mitsubishi Montero Limited.

The CUSC does not change from vehicle-to-vehicle. This reflects Consumers Union's reason for developing this maneuver, as a test of emergency handling. On an actual road, if an obstacle suddenly intrudes into a vehicle's lane requiring emergency maneuvering to avoid, the parameters of the intrusion (distance ahead of oncoming vehicle at which the intrusion begins, amount of intrusion) do not depend on the characteristics of the oncoming vehicle. In other words, if a child runs out in front of you, he or she does not run out sooner because your vehicle is bigger or wider.

[1] These maneuvers include the Fishhook 1b, the Path Corrected Limit Lane Change, the ISO 3888 Part 2 Double Lane Change, and the Consumers Union Short Course Double Lane Change.

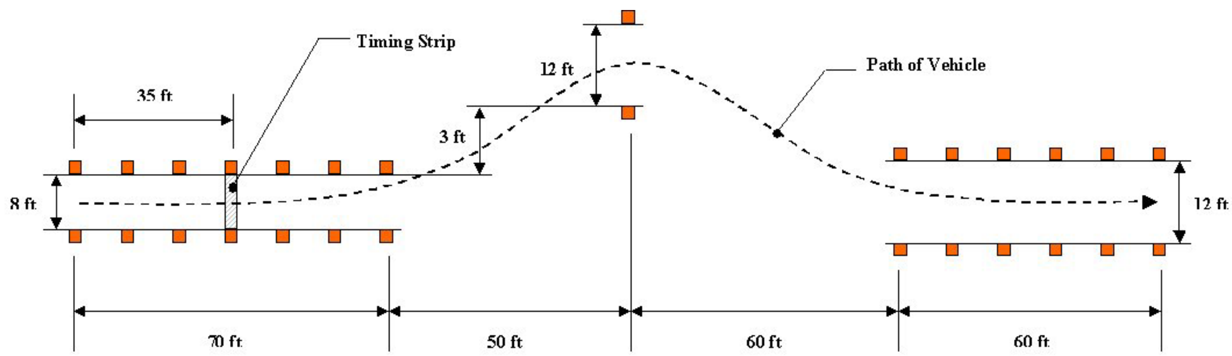

Figure 12.1. Consumers Union Short Course dimensions.

12.2 Consumers Union Short Course Maneuver Description

To begin this maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. As the vehicle approached the entrance lane, the driver released the throttle so as to achieve a desired target speed as the vehicle passed over a timing strip 35 feet from the entrance of the first lane (see Figure 12.1). No throttle input or brake application was permitted during the maneuver. The driver steered the vehicle from an entrance lane, through an offset gate, then through an exit lane. The entrance lane was four feet narrower than the exit lane to reduce driver "pre-steering."

Drivers iteratively increased maneuver entrance speed from approximately 35 mph in 1 mph increments. The iterations continued until "clean" tests could no longer be performed (the desired course could not be followed without striking or bypassing cones). Each driver was required to perform three "clean" runs at the their maximum speed. This was to assess input and output variability for tests performed by the same driver, with the same entrance speed.

Runs that were not "clean" were considered to be not valid. This differs from Consumers Union's practice. Since Consumers Union is interested in rating the emergency handling of the vehicle, for their purpose minor deviations from the specified path are not important. However, if a double lane change were to be used for determining Government dynamic rollover resistance ratings, the authors believe it is essential that the vehicle respect all course delineations.

The manner in which drivers chose to implement the 1 mph iterations was driver-dependent. Some drivers preferred to increase speed until they could no longer achieve a "clean" run. Once this threshold was reached, the driver would reduce speed slightly and perform three "clean" runs. Other drivers would perform three "clean" runs at one speed before proceeding to the next iteration. Both methods produced similar results.

To reduce any confounding effect tire wear may have on CUSC test results a new tire set was installed on each vehicle, for each driver.

Phase IV CUSC testing was only performed using test vehicles in their Nominal Load configuration.

12.3 Consumers Union Short Course Steering Input Variability

The handwheel steering variability associated with Consumers Union Short Course testing was examined in two ways:

1. The variability of the three drivers, considered as a group. This was accomplished by comparing tests performed at the maximum overall "clean" run entrance speed attained by each driver for a particular vehicle. This assessment was therefore based on a total of three tests per vehicle. These tests usually, but not always, included one of the three tests used to evaluate individual driver variability, as explained below.

2. Individual driver variability. For each driver, this assessment was based on the three "clean" tests performed with the fastest but most similar maneuver entrance speeds[2]. This was accomplished by requiring the drivers to perform three tests with nearly equal maneuver entrance speeds. So as to insure maneuver severity would be as great as possible, the drivers were instructed to perform these tests at their maximum attainable "clean" run entrance speed for a given vehicle.

   Individual driver variability analyses were based on a total of nine tests per vehicle, three per driver. Generally speaking, one of the three tests used to assess individual driver variability was also performed at that driver's maximum overall entrance speed. This is explained in greater detail in Section 12.6.3.

12.3.1 Steering Input Variability at the Maximum Overall Entrance Speeds

Table 12.1 summarizes steering input data collected during CUSC tests performed at the maximum overall "clean" run entrance speed of each driver. The ranges of steering angles at each of the three major handwheel peaks are provided along with the corresponding averages and standard deviations. As expected, the variability of these steering angles was much greater than with the steering machine. A substantial range of values was apparent for each of the three major peaks in the steering.

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[2] The "three "clean" tests performed at the fastest but most similar maneuver entrance speeds" does not necessarily mean the "three fastest overall "clean" entrance speeds." The term "most similar" was quantified by comparing the standard deviations of groups of three maneuver entrance speeds for a particular driver. The group of three "clean" tests whose entrance speeds were each nearest of the maximum attainable "clean" entrance speed of that driver (for a given vehicle) with the lowest standard deviation was defined as the "fastest but most similar."

Handwheel steering angle variability was quantified by considering standard deviations of the data (reported as percentages of the mean values in Table 12.1). Overall, Ford Escape results were the most disparate; the standard deviations associated with two of the three-handwheel peaks were the greatest of the Phase IV vehicles.

Generally speaking, steering angle variability increased with each successive steering peak. The extent to which these increases occurred depended on the vehicle and peak being considered. There were two exceptions to this trend. When the Toyota 4Runner was tested with disabled stability control, the standard deviations of the Initial Steer and Reversal #1 steering angles were higher than that associated with the Reversal #2 steering. When the Chevrolet Blazer was tested, the standard deviation of the Initial Steers were over twice of that associated with Reversal #1 steering, but 38 percent less than that associated with Reversal #2 steering.

The overall minimum and maximum Initial Steers used for the Phase IV vehicles (during tests performed at the maximum entrance speed attained by the drivers) differed from 40 to 122 degrees. Reversal #1 steering angles were more disparate, differing from 71 to 147 degrees. The smallest range of Reversal #2 steering angles was 58 degrees, however, this range varied as much as 257 degrees.

Table 12.1. Handwheel Angle Peaks During "Clean" CUSC Tests Performed at Maximum Maneuver Entrance Speed in the Nominal Vehicle Configuration.

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)
Toyota 4Runner	Enabled	247 – 308	280	**10.9**	380 – 478	433	**11.4**	192 – 342	274	**27.8**
	Disabled	228 – 280	263	**11.4**	354 – 450	393	**12.8**	250 – 308	277	**10.4**
Chevrolet Blazer	N/A	218 – 340	287	**21.9**	334 – 405	363	**10.2**	235 – 492	366	**35.1**
Ford Escape	N/A	239 – 279	259	**7.8**	289 – 436	339	**24.7**	238 – 464	326	**36.9**
Mercedes ML320	Enabled	225 – 268	246	**8.8**	306 – 400	346	**14.1**	255 – 399	345	**22.7**
	Disabled	206 – 275	245	**14.4**	229 – 325	289	**18.2**	217 – 411	313	**31.0**

12.3.2 Steering Input Variability of Individual Drivers

To assess each driver's individual steering input variability, the drivers were required to perform three tests at an entrance speed for which they could just complete the course without striking or bypassing any cones. Figure 12.2 presents nine handwheel inputs (angles and rates) used by the drivers during evaluation of the Chevrolet Blazer. The variability of these inputs was similar, for each driver, to that during tests performed with the other vehicles.

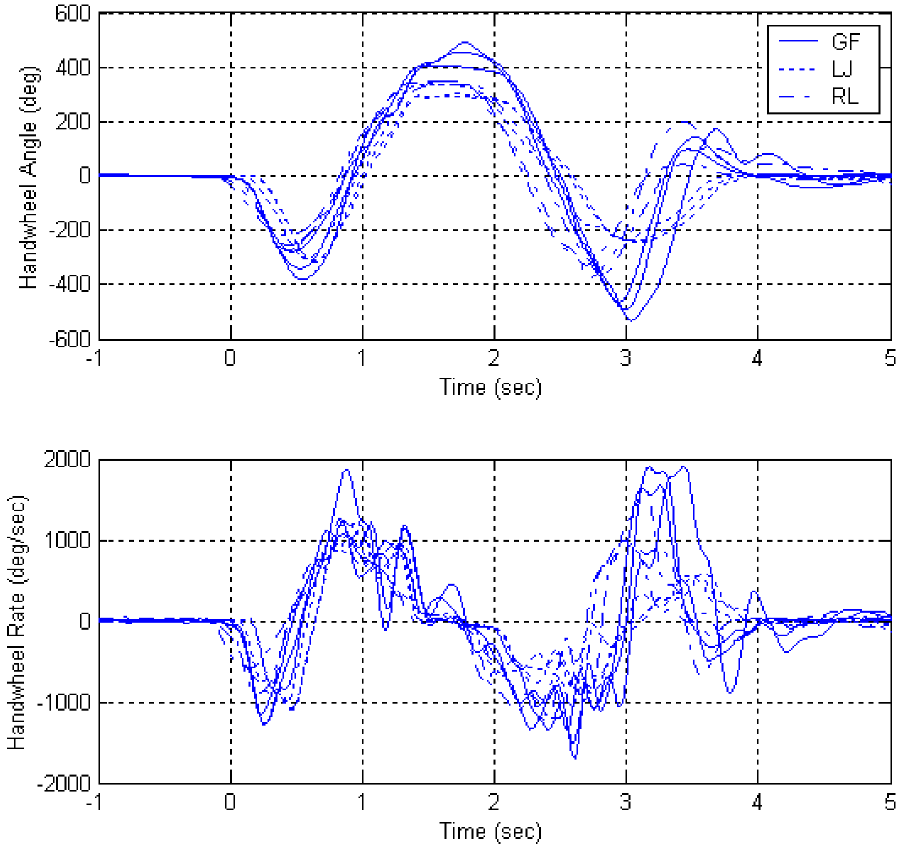

Figure 12.2. Handwheel steering variability of nine "clean" Consumers Union Short Course tests performed by three drivers with the Chevrolet Blazer. (Each set of initials represents a different driver.)

The handwheel data presented in Figure 12.2 were recorded during tests performed at the highest, yet most similar "clean" maneuver entrance speeds attainable by each driver for one vehicle. Figure 12.3 features this data for each Phase IV vehicle, and presents it in a way that more clearly illustrates the range of handwheel steering angles produced during tests performed by each driver with their fastest, but most similar, maneuver entrance speeds. The small horizontal lines plotted on each vertical band indicate the average steering angle for each range.

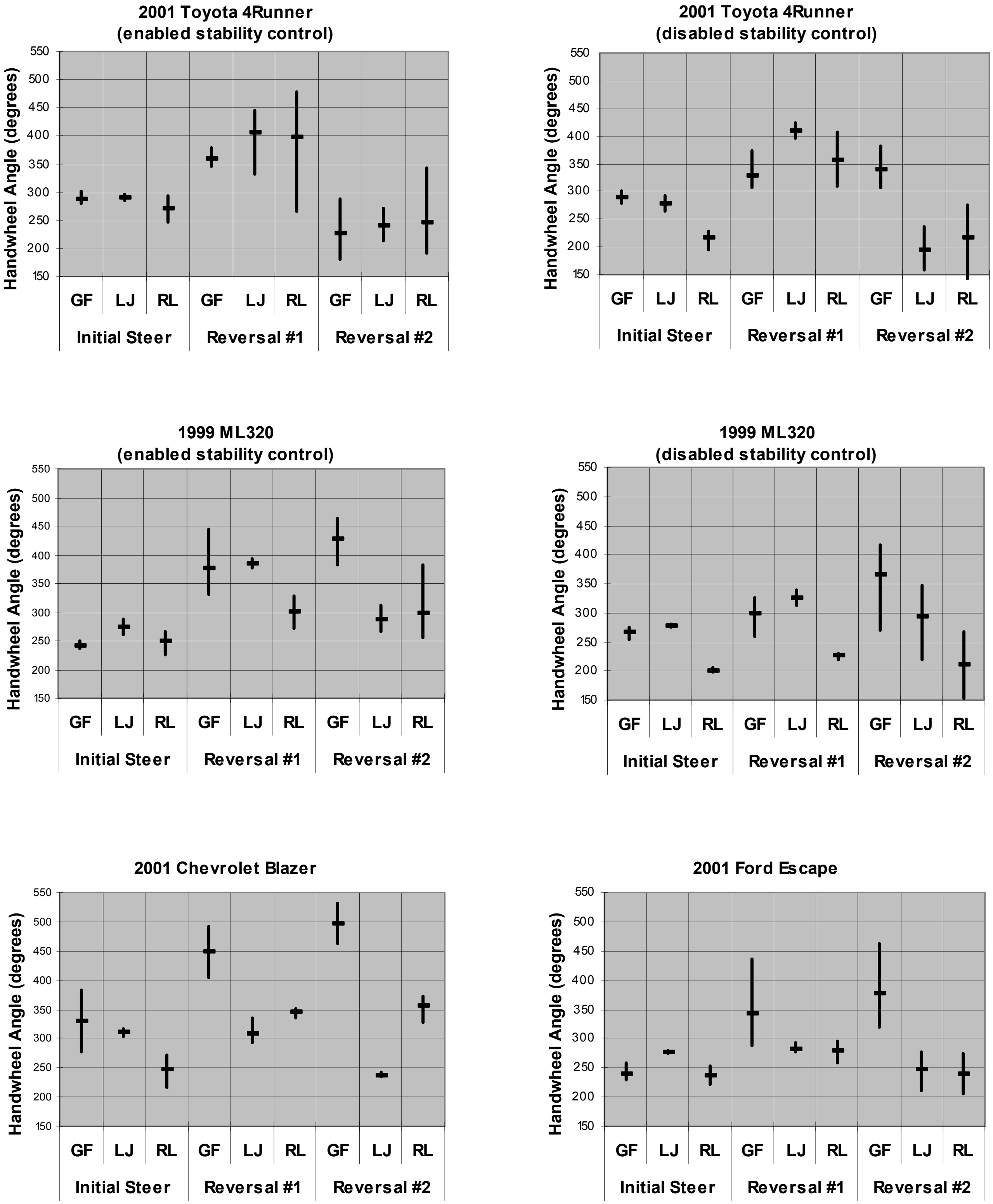

Figure 12.3. Handwheel steering angle variability during Consumers Union Short Course testing. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds. (Each set of initials represents a different driver.)

12.3.3 Effect of Stability Control on Steering Input Variability

The Toyota 4Runner and Mercedes ML320 were tested with stability control both enabled and disabled. As such, it was possible to examine the effect of stability control on the steering input variability of these vehicles using the data in Table 12.1. Recall that these data were recorded during tests performed at the overall maximum maneuver "clean" entrance speeds attained by each test driver.

In the case of the 4Runner, the ranges of Initial Steer and Reversal #1 steering angles were narrower when stability control was enabled. When the 4Runner tests performed with enabled stability control, the average Initial Steer and Reversal #1 values were 17 and 40 degrees *less* that those produced with disabled stability control, respectively. Conversely, the average Reversal #2 steering angles were nearly equal regardless of stability control operational status, differing by only 3 degrees.

For the ML320, the range of steering angles at each of the three primary handwheel peaks was narrower when stability control was enabled. Furthermore, the average steering inputs of the tests performed at the overall maximum maneuver entrance speeds at each peak were greatest with enabled stability control. The average Initial Steers were nearly equal regardless of stability control operational status, differing by only 1 degree. For the ML320 tests performed with enabled stability control, the average Reversal #1 and #2 steering angles were 57 and 32 degrees greater that those produced with disabled stability control, respectively.

12.4 Consumers Union Short Course Vehicle Speed Variability

As explained in Section 12.3, each driver performed three "clean" runs at their fastest, but most consistent, maneuver entrance speed for each vehicle. These repetitions permitted vehicle speed repeatability assessment. This assessment included three considerations:

- Ability of the drivers to achieve a desired maneuver entrance speed
- Effect of handwheel steering input variability
- Effect of stability control on vehicle speed, if applicable

12.4.1 Entrance Speed Variability

Although the burden placed on the drivers during CUSC testing was greater than that imposed by maneuvers using the steering machine, entrance speed repeatability was very good. When all groups of three tests performed at the fastest, most consistent "clean" run entrance speeds were considered (per driver and vehicle), the greatest speed differential was 1.1 mph. This was in agreement with maneuver entrance speed variability during other Phase IV Characterization and Dynamic Rollover Propensity maneuvers.

12.4.2 Effect of Handwheel Input Variability

While the approaches just prior to maneuver execution featured good repeatability, the manner in which vehicle speed was scrubbed during the maneuver varied from test-to-test. Steering input variability was largely responsible for this phenomenon.

Figure 12.4 demonstrates how handwheel steering angle variability affected vehicle speed during CUSC tests performed with the Chevrolet Blazer. In this example, the Reversal #1 and Reversal #2 peak steering angles used by Driver GF were much greater than those of Drivers LJ or RL. Although the average entrance speed of the three tests performed by Driver GF (38.9 mph) was between those of Drivers LJ (37.6 mph) and RL (40.2 mph), the vehicle speeds associated with GF's tests diverged from those of the other drivers after completion of Reversal #1.

To better illustrate this point, Test 1689 has been highlighted. Of the nine tests presented in Figure 12.4, Test 1689 contains the largest Reversal #1 and #2 peak steering angles. As a result, the exit speed of this test was lowest of tests shown in Figure 12.4.

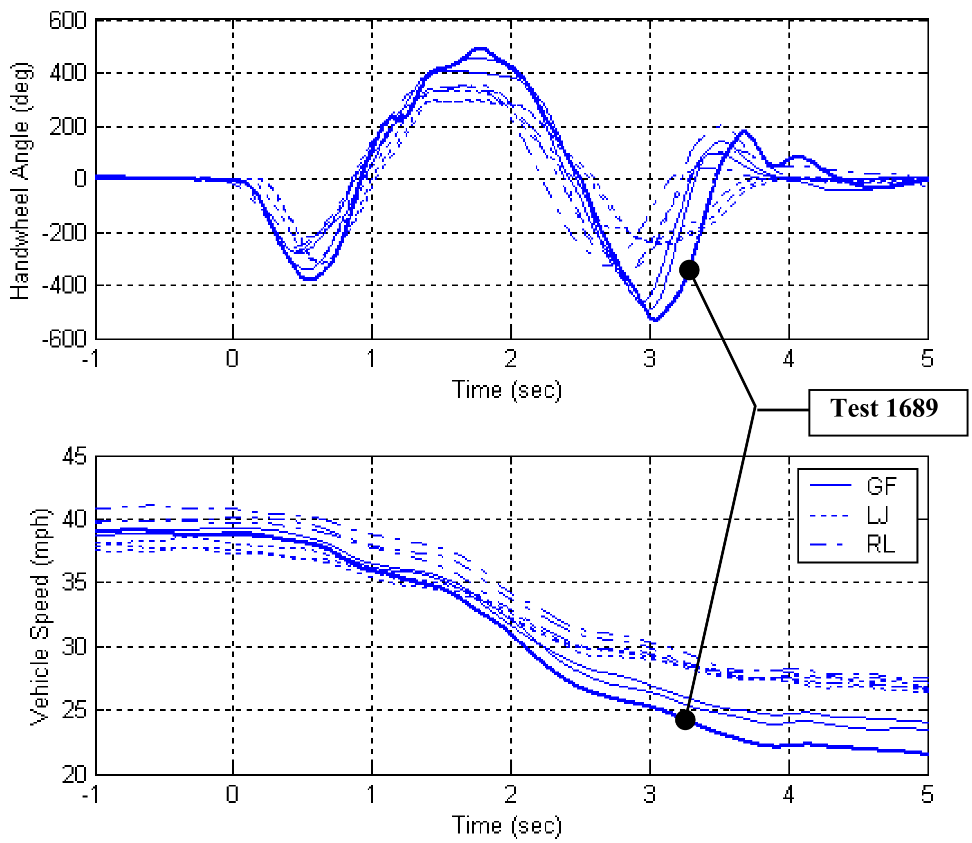

Figure 12.4. Handwheel steering angle and vehicle speed during "clean" CUSC tests performed with the Chevrolet Blazer. Note how handwheel steering angle variability affected speed vehicle. (Each set of initials represents a different driver.)

12.4.3 Effect of Stability Control on Vehicle Speed

Like steering input variability, stability control intervention had a pronounced effect on the vehicle speed variability during CUSC testing. When all groups of the three “clean” tests performed at the fastest, most consistent entrances speeds were considered[3], the exit speed of every test performed with disabled stability control was greater than any performed with enabled stability control, even if the maneuver entrance speeds were slightly higher with enabled stability control. Results for the Toyota 4Runner and Mercedes ML320 were in good agreement, however, the speed differentials between tests performed with enabled and disabled stability control were generally greater for the 4Runner.

Figure 12.5 presents handwheel steering angle and vehicle speed data for six “clean” CUSC tests executed with the Toyota 4Runner. Three of these tests were performed with enabled stability control, and began with entrance speeds of 36.6, 36.6, and 36.8 mph. The tests performed with disabled stability control began at 35.3, 34.9, and 35.1 mph. Driver LJ was responsible for all steering inputs presented in Figure 12.5. The vehicle speed variability for this driver was representative of that seen for the other drivers.

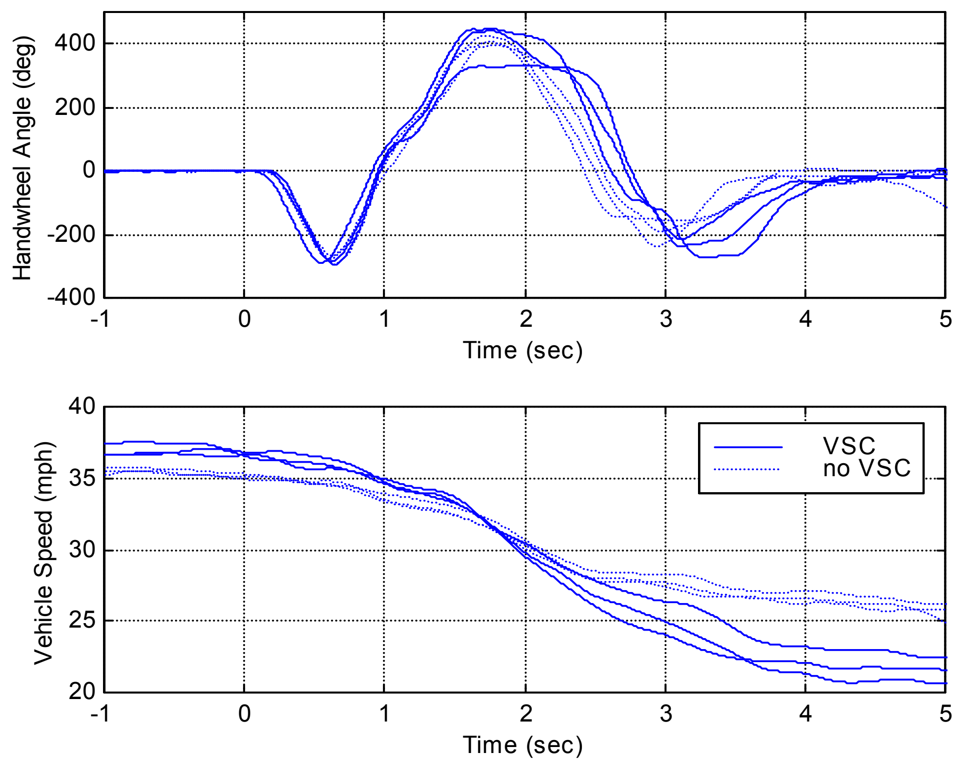

Figure 12.5. Handwheel and vehicle speed data for six “clean” Consumers Union Short Course tests performed with the Toyota 4Runner (Driver LJ).

[3] Twelve groups of three tests were used in this analysis, six for the Toyota 4Runner and six for the Mercedes ML320. In each group of six, three groups (one group per driver) were performed with enabled stability control and three with it disabled. Therefore, this analysis compared the exit speeds of 18 tests performed with enabled stability control to exit speeds for 18 performed with disabled stability control.

In this example, the average maneuver entrance speeds of tests performed with enabled stability control were greater than those used when it was disabled (36.6 versus 35.1 mph). However, the maneuver exit speeds with enabled stability control were each less than those when stability control had been disabled. At the completion of the maneuver[4], the exit speeds with enabled stability control were 14.1 to 16.0 mph (38.5 to 43.7 percent) lower than their respective maneuver entrance speeds. When stability control was disabled, exit speeds were 9.1 to 10.0 mph (25.7 to 28.7 percent) lower than their respective maneuver entrance speeds. At the completion of the maneuver, the average vehicle speed with disabled stability control was 25.7 mph. When stability control was enabled, the average exit speed was 21.6 mph, 16.0 percent lower than when it was disabled.

Enabling stability control did not necessarily result in the highest "clean" run entrance speeds. Figure 12.6 presents six tests performed by Driver GF with the Toyota 4Runner. In this example, the fastest "clean" maneuver entrance speeds were achieved when stability control was disabled (37.4 mph with disabled stability control versus 36.0 mph when it was enabled).

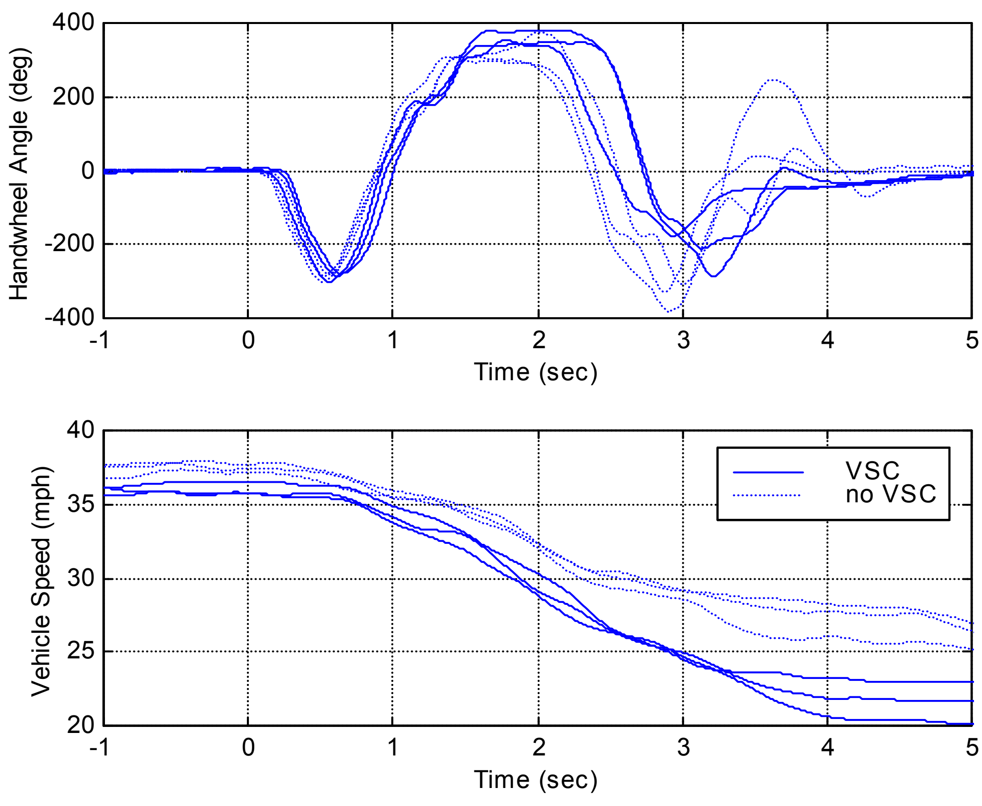

Figure 12.6. Handwheel steering angle and vehicle speed data for six "clean" Consumers Union Short Course tests performed with the Toyota 4Runner (Driver GF).

[4] To provide a basis for comparison, Consumers Union Short Course maneuver completion was taken to be five seconds after the front of the vehicle had reached the timing strip.

Over the duration of the Figure 12.6 tests, overall vehicle speed generally remained the highest with disabled stability control, and all "clean" tests performed with disabled stability control were concluded at higher speeds than those performed with it enabled. At maneuver completion, the exit speeds with enabled stability control were 12.9 to 16.5 mph (36.0 to 45.0 percent) lower than their respective maneuver entrance speeds. When stability control was disabled, exit speeds were 10.2 to 12.2 mph (27.3 to 32.7 percent) lower than their respective maneuver entrance speeds. At the completion of the maneuver, the average vehicle speed with disabled stability control was 26.1 mph. When stability control was enabled, the average exit speed was 21.5 mph, 17.8 percent lower than when it was disabled.

12.5 Consumers Union Short Course Output Variability

In a manner identical to that used to analyze steering input variability, the output variability associated with CUSC testing was assessed in two ways:

1. The lateral acceleration variability during tests performed at the maximum overall "clean" maneuver entrance speed of each driver, per vehicle.

2. The lateral acceleration variability during tests performed at the three highest, most similar maneuver "clean" entrance speeds performed by individual drivers, per vehicle.

12.5.1 Output Variability of Tests Performed at the Maximum Overall Entrance Speeds

Table 12.2 presents lateral acceleration data from CUSC tests performed at the maximum overall "clean" entrance speed of each driver. The ranges of lateral accelerations at each of the three major handwheel peaks are provided along with the corresponding averages and standard deviations. As expected, the variability of these inputs was much greater than with the steering machine. A substantial range of values was apparent for each of the three major handwheel peaks.

Individual driver variability analyses were based on a total of nine tests per vehicle, three per driver. Generally speaking, one of the three tests used to assess individual driver variability was also performed at that driver's maximum overall entrance speed. This is explained in greater detail in Section 12.6.3.

Table 12.2. Lateral Acceleration Peaks During "Clean" CUSC Tests Performed at Maximum Maneuver Entrance Speed in the Nominal Vehicle Configuration.

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)
Toyota 4Runner	Enabled	0.74 – 0.77	0.75	**2.1**	0.71 – 0.74	0.72	**1.9**	0.49 – 0.69	0.60	**17.1**
	Disabled	0.72	0.72	**0**	0.77 – 0.84	0.81	**4.3**	0.69 – 0.73	0.72	**3.5**
Chevrolet Blazer	N/A	0.68 – 0.84	0.76	**10.3**	0.77 – 0.88	0.84	**6.8**	0.68 – 0.74	0.72	**4.5**
Ford Escape	N/A	0.71 – 0.78	0.75	**4.9**	0.87 – 0.96	0.92	**4.6**	0.68 – 0.79	0.73	**8.1**
Mercedes ML320	Enabled	0.74 – 0.77	0.75	**2.3**	0.83 – 0.96	0.88	**7.9**	0.75 – 0.80	0.78	**3.4**
	Disabled	0.76 – 0.77	0.76	**1.1**	0.83 – 0.86	0.85	**1.7**	0.66 – 0.77	0.71	**7.1**

Unlike the steering input variability discussed previously, lateral acceleration response variability did not necessarily increase with each successive steering angle peak. In fact, this was the case only for one vehicle (the Mercedes ML320 with disabled stability control). In the case of the Ford Escape and Toyota 4Runner with enabled stability control, the lateral acceleration variability produced with Reversal #1 steering was less than that associated with Initial Steer or Reversal #2 steering. In the case of the 4Runner with disabled stability control and the ML320 with enabled stability control, the lateral acceleration variability produced with Reversal #1 steering was greater than that associated with Initial Steer and Reversal #2 steering. The lateral acceleration variability of the Chevrolet Blazer decreased with at each successive handwheel angle peak (highest in response to the Initial Steer, lowest in response to Reversal #2 steering).

The range of average lateral accelerations due to the Initial Steer for the Phase IV vehicles differed by 0.04 g (0.72 to 0.76 g). The range of average lateral accelerations due to the Reversal #1 steering was more disparate, differing by 0.20 g (0.72 to 0.92 g). The average lateral accelerations contained within the range associated with Reversal # 2 inputs differed by 0.18 g (0.60 to 0.78 g).

12.5.2 Lateral Acceleration Output Variability of the Individual Drivers

CUSC test output variability was assessed by considering lateral acceleration, roll angle, yaw rate, and roll rate responses produced during three "clean" runs performed at the fastest, most consistent maneuver entrance speeds of each driver. Figure 12.7 provides an example of these data. These data were referenced in time to the instant the vehicle reached the course's timing strip (recall Figure 12.1). The variability of these outputs was similar, for each driver, to that of tests performed with the other vehicles.

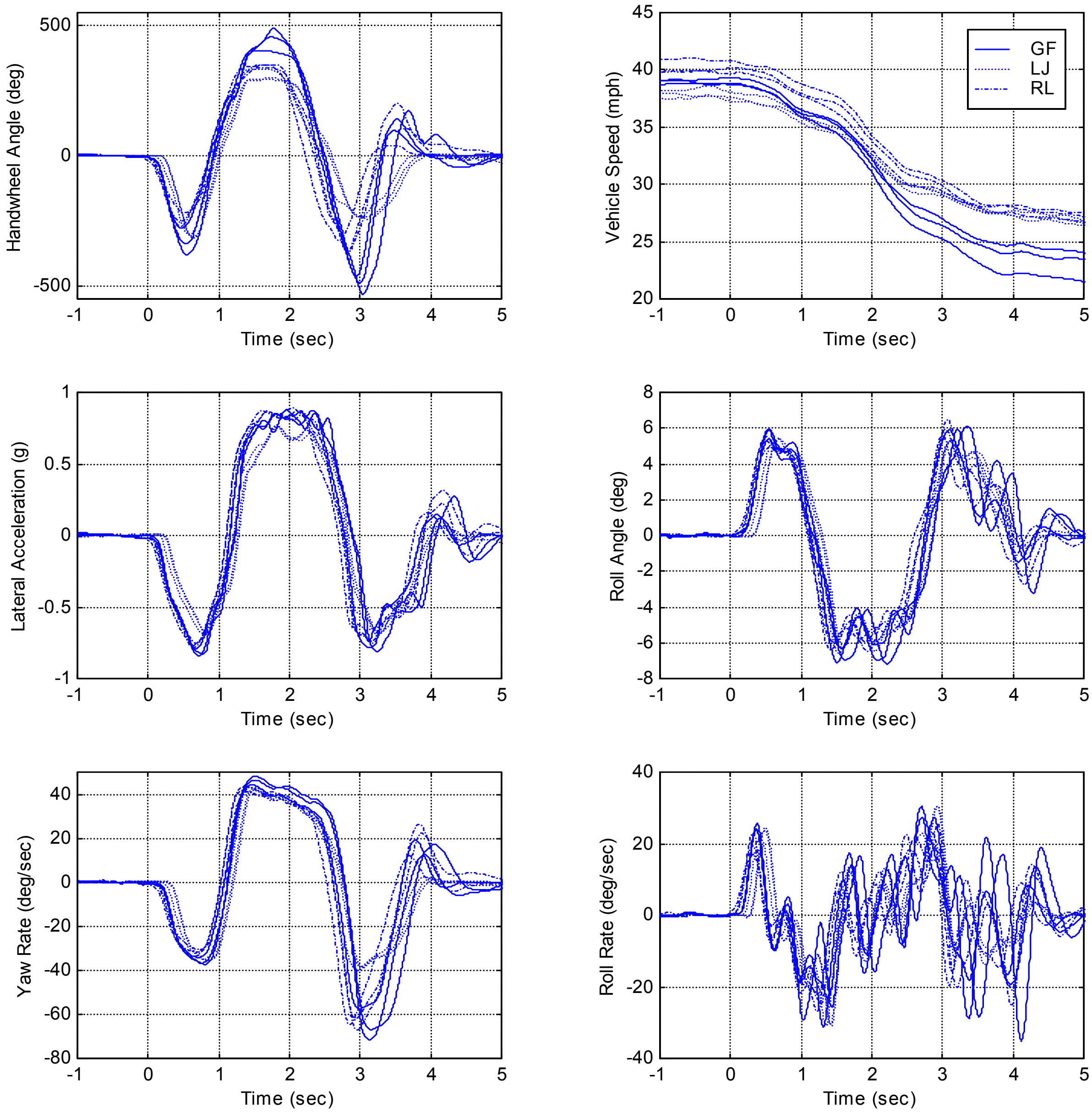

Figure 12.7. Test output repeatability for nine "clean" Consumers Union Short Course performed by three drivers with the Chevrolet Blazer. (Each set of initials represents a different driver.)

The data presented in Figure 12.7 were recorded during CUSC tests performed by the drivers at their highest, but most consistent, "clean" maneuver entrance speeds for one vehicle. Figure 12.8 shows lateral acceleration data for each Phase IV vehicle, and presents it in a way that more clearly illustrates the range of lateral accelerations produced by each driver (when compared to Figure 12.7). Each vertical band represents the range of responses produced during tests performed by a particular driver during test started with the fastest, but most similar, "clean" maneuver entrance speeds. The small horizontal lines plotted on each vertical band indicate the average lateral acceleration contained in each range.

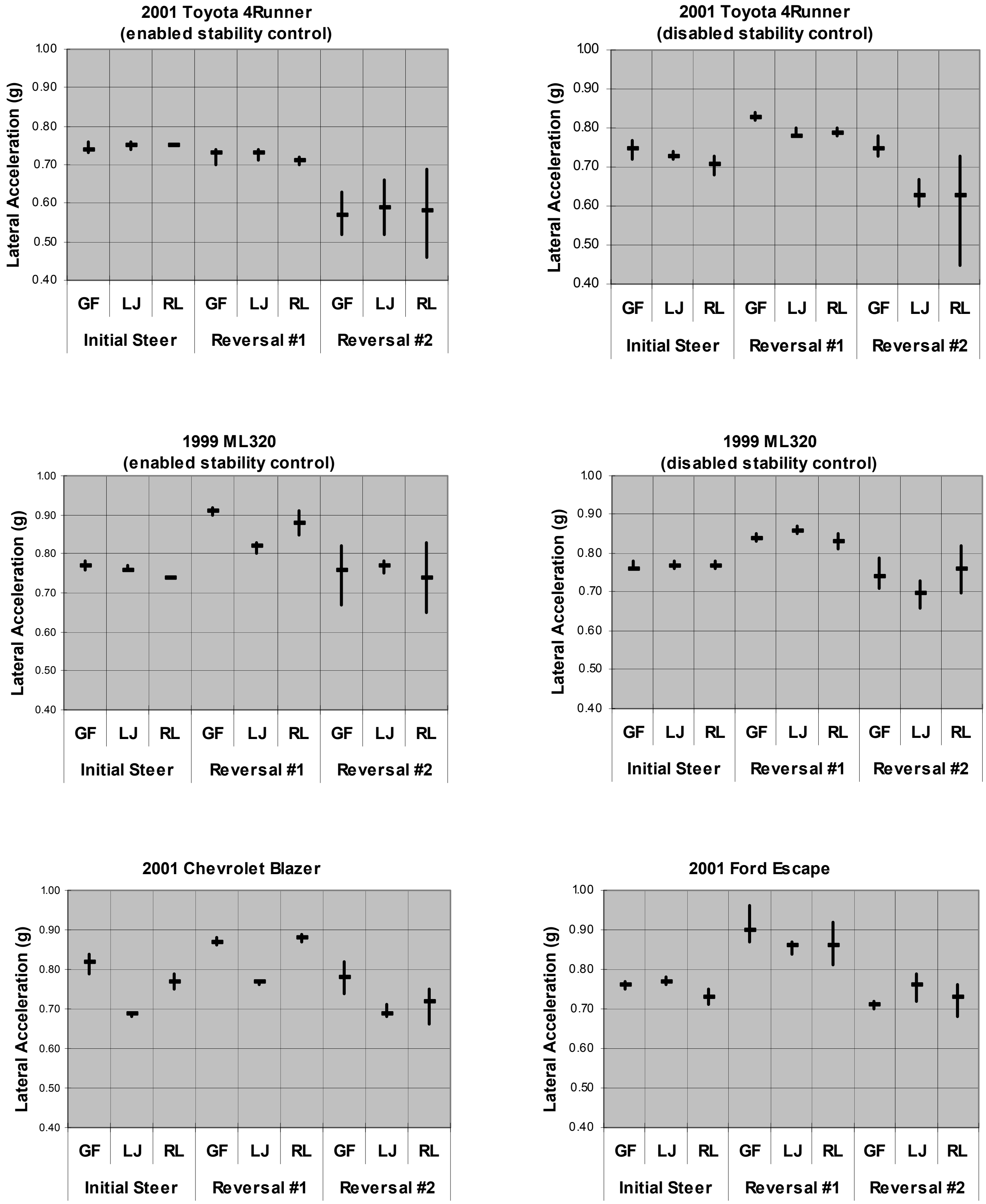

Figure 12.8. Lateral acceleration output variability during Consumers Union Short Course testing. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds. (Each set of initials represents a different driver.)

12.5.3 Effect of Stability Control on Lateral Acceleration Output Variability

The Toyota 4Runner and Mercedes ML320 were evaluated with enabled and disabled stability control. As such, it was possible to examine the effect of stability control on the lateral acceleration output variability of these vehicles using the data presented previously in Table 12.2. Recall that these data were recorded during tests performed at the overall maximum maneuver "clean" entrance speeds attained by each driver.

For the Toyota 4Runner the range of lateral accelerations due to the Initial Steer and Reversal #2 steering angles were narrower when stability control was disabled. The lateral acceleration variability associated with Reversal #1 was lower with enabled stability control.

In the case of the 4Runner, the average lateral acceleration due to the Initial Steer was greater with enabled stability control, differing by 0.03 g (4.2 percent) from the average lateral acceleration due to disabled stability control. Conversely, the average lateral accelerations associated with Reversal #1 and #2 were 0.09 and 0.12 g (12.5 and 20.0 percent) greater when stability control was disabled.

For the Mercedes ML320 the range of lateral accelerations due to the Initial Steer and Reversal #1 steering angles were narrower when stability control was disabled. In fact, the ranges of disabled stability control lateral accelerations due to the Initial Steer and Reversal #1 steering angles were entirely contained within the respective range established with enabled stability control results. The lateral acceleration variability associated with Reversal #2 steering was lower with enabled stability control.

Unlike the Toyota 4Runner, the average lateral acceleration produced by the Mercedes ML320 due to the Initial Steer was greater with disabled stability control, differing by 0.01 g (1.3 percent) from the average lateral acceleration produced with enabled stability control. Conversely, the average lateral accelerations associated with Reversal #1 and #2 steering were 0.03 and 0.07 g (3.5 and 9.9 percent) greater when stability control was enabled.

12.6 Consumers Union Short Course Results

The rating metric used by NHTSA for the CUSC was the maximum entry speed into the test course at which a driver successfully achieved a "clean" run. Note that this is not the rating metric used by Consumers Union. Consumers Union performs subjective rating of the emergency handling capability of vehicles, and rates the safety of vehicles exhibiting large amounts of two-wheel lift in this maneuver as "unacceptable."

Consumers Union did not design the Short Course to directly measure dynamic rollover propensity. Rather, it was designed to facilitate the observation of the way a vehicle responds to being driven up to, and beyond, its limits. If two-wheel lift occurs during a CUSC test, the response is considered to be indicative that vehicle might respond in the same way in an emergency crash avoidance situation.

12.6.1 Overall Maximum Maneuver Entrance Speed

Table 12.3 summarizes the maximum "clean" run entrance speeds for each vehicle achieved by each driver during Phase IV CUSC testing.

Overall, the range of maximum maneuver entrance speeds was quite narrow (i.e., when all of the Phase IV vehicles were considered together). The lowest maximum entrance speed was 35.7 mph, for Driver LJ during Toyota 4Runner testing with disabled stability control. The overall maximum entrance speed used by any driver, for any vehicle evaluated with the CUSC, was 40.7 mph. Driver RL achieved this speed during tests performed with the Chevrolet Blazer. The difference between the slowest and fastest overall maximum "clean" entrance speeds was only 5.0 mph, differing by 14.0 percent.

Table 12.3. Maximum Entrance Speeds Achieved by Each Driver During "Clean" CUSC Tests Performed in the Nominal Vehicle Configuration.

Driver	Toyota 4Runner		Chevrolet Blazer	Ford Escape	Mercedes ML320	
	VSC	No VSC			ESP	No ESP
GF	36.5	37.7	39.3	37.0	38.8	36.7
LJ	37.4	35.7	38.1	37.1	37.1	36.6
RL	37.8	37.8	40.7	40.5	39.2	38.3
Average	37.2	37.1	39.4	38.2	38.4	37.2
Std Dev	0.7	1.2	1.3	2.0	1.1	1.0
Min - Max	**1.3**	**2.1**	**2.6**	**3.5**	**2.1**	**1.7**

Note: All speed values are in mph.

When stability control was enabled, the maximum "clean" entrance speeds of the Toyota 4Runner ranged from 36.5 to 37.8 mph, differing by up to 1.3 mph (3.6 percent). When stability control was disabled, the range of entrance speeds (35.7 to 37.8 mph) differed to a greater extent, up to 2.1 mph (5.9 percent).

The maximum maneuver "clean" entrance speeds of the Chevrolet Blazer ranged from 38.1 to 40.7 mph, differing by up to 2.6 mph (6.8 percent).

The range of speeds for the Ford Escape was 37.0 to 40.5 mph. The maximum "clean" entrance speeds differed by up to 3.5 mph (9.5 percent).

When stability control was enabled, the maximum "clean" entrance speeds of the Mercedes ML320 ranged from 37.1 to 39.2 mph, differing by up to 2.1 mph (5.7 percent). When stability control was disabled, the range of entrance speeds (36.6 to 38.3 mph) differed to a lesser extent, up to 1.7 mph (4.6 percent).

12.6.2 Effect of Stability Control on Overall Maximum Entrance Speed

Enabling stability control during tests performed with the Toyota 4Runner did not necessarily allow each driver to attain their maximum maneuver "clean" entrance speed. The maximum "clean" entrance speed of Driver LJ was 1.7 mph (4.8 percent) greater than that achieved when stability control was disabled. Regardless of whether stability control was enabled or disabled, Driver RL attained equal maximum "clean" entrance speeds with the 4Runner. Driver GF, however, was able to achieve a 1.2 mph (3.3 percent) greater maximum maneuver "clean" entrance speed with disabled stability control.

All drivers were able to achieve their highest overall maximum maneuver "clean" entrance speeds with enabled stability control during Mercedes ML320 testing. In agreement with the Toyota 4Runner results, these differences were small. The maximum "clean" entrance speeds of the tests performed by Drivers GF, LJ, and RL were 2.1, 0.5, and 0.9 mph (5.7, 1.4, and 2.3 percent) greater, respectively, than those achieved when stability control was disabled.

12.6.3 Comparison of Maximum and Average Maneuver Entrance Speeds

Table 12.4 compares each driver's maximum overall "clean" entrance speed, for a particular vehicle, to the average of the three highest, most consistent maneuver "clean" entrance speeds achieved by that driver. If the *maximum* "clean" entrance speed of a driver related well to the *average* speed of the highest, most consistent maneuver "clean" entrance speeds it is likely the full potential of that driver was realized during CUSC testing.

Regardless of the vehicle or driver being considered, the average speeds presented in Table 12.4 were each within 1.2 mph (3.3 percent) of the maximum maneuver "clean" entrance speeds. The fact these differences were low was not surprising, given that the three tests performed at the highest, most consistent "clean" entrance speeds generally contained the test performed at the maximum overall "clean" entrance speed. There were only three exceptions to this. During tests performed with the Toyota 4Runner (with stability control both enabled and disabled) and the Mercedes ML320 (disabled stability control), the maximum "clean" entrance speed achieved by Driver LJ was greater than each of the three highest, most consistent maneuver "clean" entrance speeds.

Table 12.4. Comparison of Average vs. Maximum Maneuver Entrance Speeds for "Clean" CUSC Tests Performed in the Nominal Vehicle Configuration.

Driver	Toyota 4Runner, VSC (mph)			Toyota 4Runner, no VSC (mph)			Chevrolet Blazer (mph)			Ford Escape (mph)			Mercedes ML320, ESP (mph)			Mercedes ML320, no ESP (mph)		
	Ave (mph)	Max (mph)	% Increase	Ave (mph)	Max (mph)	% Increase	Ave (mph)	Max (mph)	% Increase	Ave (mph)	Max (mph)	% Increase	Ave (mph)	Max (mph)	% Increase	Ave (mph)	Max (mph)	% Increase
GF	36.0	36.5	**1.4**	37.4	37.7	**0.8**	38.9	39.3	**1.0**	36.7	37.0	**0.8**	38.0	38.8	**2.1**	36.6	36.7	**0.3**
LJ	36.6	37.4	**2.2**	35.1	35.7	**1.7**	37.6	38.1	**1.3**	36.7	37.1	**1.1**	36.3	37.1	**2.2**	36.2	36.6	**1.1**
RL	37.4	37.8	**1.1**	36.6	37.8	**3.3**	40.2	40.7	**1.2**	40.0	40.5	**1.3**	38.7	39.2	**1.3**	38.1	38.3	**0.5**

12.6.4 Two-Wheel Lift

No two-wheel lift occurred during any "clean" run.

The only instance of two-wheel lift produced during CUSC testing occurred when a driver who was familiar with the course, but was not one of the three test drivers, attempted to perform the maneuver at a high speed. When this driver entered the course at 42.6 mph with the Chevrolet Blazer, two-wheel lift great enough to contact both left-side outrigger castors was produced. It is very important to recognize this test was not valid. The driver used a tire set from a previous driver, and was performed at a speed for which successful completion of the course was highly unlikely, and numerous cones were hit. The test is mentioned only to demonstrate that two-wheel lift was only realized during a non-valid test using the CUSC.

12.6.5 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact occurred during CUSC testing, regardless of vehicle or driver.

12.7 Consumers Union Short Course Maneuver Assessment

Using the criteria presented in Chapter 2, the authors have rated Consumers Union Short Course testing in the following manner:

Objectivity and Repeatability = Bad

Since the test driver generates steering inputs for the Consumers Union Short Course Double Lane Change maneuver, vehicle performance in this maneuver depends upon the skill of the test driver, the steering strategy used by the test driver, plus random run-to-run fluctuations.

As Table 12.1 and Figures 12.2 and 12.3 demonstrate, both substantial driver-to-driver differences and substantial within driver run-to-run differences in the steering inputs occurred during the Phase IV CUSC testing. These differences tended to increase as the maneuver progressed. That said, these differences might not necessarily matter for the purposes of determining Rollover Resistance Ratings. What really matters are driver-to-driver and run-to-run differences in vehicle outputs, specifically how they influence the vehicle rating metric.

The rating metric used by NHTSA was the maximum maneuver entrance speed for which a driver successfully achieved a "clean" run (i.e., none of the cones delineating the course were struck or bypassed)[5]. Using three test drivers, the overall range of maximum maneuver "clean" entrance speeds varied from 1.3 mph for the Toyota 4Runner with enabled stability control to 3.5 mph for the Ford Escape. The average range was 2.2 mph. While these may seem like small

[5] Note that this is not the rating metric used by Consumers Union for this maneuver. Consumers Union uses the Short Course to subjectively rate the emergency handling capability of vehicles. If a vehicle produces large amounts of two-wheel lift during tests performed with the Short Course, Consumers Union gives that vehicle an "unacceptable" safety rating, regardless of the maximum valid maneuver entrance speed the vehicle was able to achieve.

ranges, the entire range of maximum attainable maneuver “clean” entrance speeds was only 5.0 mph when all of the Phase IV vehicles were considered. Since the Phase IV vehicles are believed to be representative of typical, current generation sport utility vehicles, these results imply the maximum valid maneuver “clean” entrance speeds achievable for most sport utility vehicles will fall within this 5.0 mph range. Therefore, driver-to-driver variability accounts for an average of 44 percent of the rating metric’s range. The range of maximum maneuver “clean” entrance speeds of the Ford Escape suggests that this variability can account for up to 70 percent of the rating metric range.

Table 12.5 shows a rank ordering of the Phase IV rollover test vehicles based on the maximum “clean” entrance speeds achieved by the three test drivers. Note that “1” is the best rank and “6” the worst. This table clearly shows the problem caused by driver-to-driver variability combined with the small range of metric values. While the Chevrolet Blazer attained the best ranking from all three drivers, the ranking for the Toyota 4Runner with stability control enabled varied from second best to worst.

Table 12.5. Vehicle Rankings Based on Maximum Achievable Entrance Speeds for “Clean” CUSC Tests Performed in the Nominal Vehicle Configuration.

Driver	Chevrolet Blazer	Ford Escape	Mercedes ML320 (ESP)	Mercedes ML320 (no ESP)	Toyota 4Runner (VSC)	Toyota 4Runner (no VSC)
GF/RS	1	4	2	5	6	3
LJ	1	3	3	5	2	6
RL	1	2	3	4	5	5

Driver skills and abilities vary with time. Although this was not directly measured in Phase IV, the authors believe that if Consumers Union Short Course was used to re-test the Phase IV vehicles, with the same drivers, the results would not be exactly reproduced. Since the rating metric range established in Phase IV was so narrow, day-to-day (or even hour-to-hour) changes in test driver performance could potentially change the maximum maneuver “clean” entrance speeds by a substantial percentage of the overall range.

Due to the problems associated with driver-to-driver variability and run-to-run (for the same driver) variability, the Objectivity and Repeatability of the Consumers Union Short Course Double Lane Change maneuver was rated as bad. However, it is important to recognize that NHTSA’s objective for this maneuver, the determination of rollover resistance ratings, is not the same as Consumers Union’s objective, the evaluation of a vehicle’s emergency handling capabilities. Handling evaluation has always been a subjective process. This appears to be a better maneuver for what Consumers Union wants to accomplish than for what the Government wants to accomplish.

Performability = Satisfactory

The procedure for performing tests with the Consumers Union Short Course was straightforward. However, as discussed above, use of this course is associated with objectivity and repeatability issues. Resolving these issues will add difficulty and complexity to the test procedure.

For example, one possibility for improving objectivity and repeatability is to use multiple drivers to perform the testing (three drivers were used during the NHTSA testing). While this should help, there are still potential problems. One exceptionally skilled test driver could generate very good performance metrics for a mediocre vehicle. If this exceptionally skilled driver did not test some other vehicle, that vehicle's performance metrics might, incorrectly, be lower than they should be. Therefore, in addition to using multiple drivers, procedures would need to be developed to ensure that drivers of approximately equal skill test every vehicle.

The Consumers Union Short Course Double Lane Change test procedure does not change as a function of the vehicle being tested. This reflects Consumers Union's reason for developing this maneuver; as a test of emergency handling. On an actual road, if an obstacle suddenly intrudes into a vehicle's lane requiring emergency maneuvering to avoid, the parameters of the intrusion (distance ahead of oncoming vehicle at which the intrusion begins, amount of intrusion) do not depend on the characteristics of the oncoming vehicle. In other words, if a child runs out in front of you, they do not run out sooner because your vehicle is bigger or wider.

Although the evaluation of emergency handling is important, and the CUSC provides one way to observe it, the Government's desire is not to evaluate emergency handling but to rate dynamic rollover propensity. For the Government's purpose, the authors believe a test maneuver should adapt to differing vehicle characteristics so as to maximize severity. In the case of a double lane change, the course layout must be modified on a per-vehicle basis so as to achieve worst-case lane geometry. Such modifications may relate to vehicle size or other characteristics. Since two-wheel lift was not detected during any CUSC test for which no course delimiting cones were struck, the authors to not believe that this layout imposes the worst-case lane geometry for the Phase IV vehicles. For these reasons, the authors can rate the Performability of the Consumers Union Short Course Double Lane Change maneuver as no better than satisfactory.

Discriminatory Capability = Very Bad

Consumers Union Short Course tests were performed with each vehicle in the Nominal Load configuration only. Despite the use of high steering angle magnitudes and production of high lateral accelerations, no two-wheel lift occurred during any "clean" run performed using the CUSC, for any of the Phase IV test vehicles. While one two-wheel lift did occur during a run that was not "clean", this should not be considered for the determination of our rollover resistance ratings. The reason is that when a run is not "clean", the path-following nature of the test is no longer meaningful. The driver could use an infinite combination of steering inputs. For example, rather than attempting to perform a "clean" run, the driver could input the fishhook steering required to produce two-wheel lift. To achieve a high maneuver entrance speed, the driver could simply drive straight through the course without any avoidance steering. Either case would simply be recorded as a "not clean" test, although the test outcomes are obviously very different.

Unlike the J-Turn and Fishhook maneuvers, the occurrence/non-occurrence of two-wheel lift cannot be used as a measure of vehicle performance for this maneuver because two-wheel lifts during "clean" runs are unlikely to occur. The rating metric used by NHTSA therefore was the maximum entry speed into the test course at which a driver successfully achieved a "clean" run. Tests performed with the Consumers Union Short Course Double Lane Change measure both the handling and rollover resistance of vehicle. Results from both J-Turn and Fishhook testing are, of course, also influenced by the handling characteristics of a vehicle. However, handling has less of a chance to dominate these maneuvers because they involve fewer major steering movements (one for a J-Turn, two for a Fishhook, and three for a Double Lane Change).

Since Consumers Union developed this maneuver to examine the emergency handling of vehicles, and because this maneuver is not as tightly constrained as the ISO 3888 Part 2 Double Lane Change course, the authors believe tests performed with the CUSC focus even more on handling than do tests performed with the ISO 3888 Part 2 Double Lane Change maneuver. Since handling and rollover resistance are inextricably intertwined in the rating produced by this maneuver (with handling being the dominating factor), the rating generated can actually improve even though the rollover resistance of a vehicle is getting worse. This reasoning explains how it was possible for each driver to achieve their highest maneuver entrance speeds with the Chevrolet Blazer despite its one-star Static Stability Factor rating and poor rollover resistance in NHTSA J-Turn and Fishhook tests.

Since tests using the Consumers Union Short Course measure some combination of vehicle handling and rollover resistance (with handling characteristics apparently dominating the measured metric values), the authors can rate the Discriminatory Capability of the Consumers Union Short Course Double Lane Change maneuver for rollover resistance (not emergency handling) as no better than very bad. Note that this maneuver has better rollover resistance Discriminatory Capability during testing performed by Consumers Union because, for Consumers Union's purposes, tests that strike cones can be considered. The Government believes that, to remove any possibility of bias, tests that strike cones cannot be considered. (Consumers Union uses other measures to ensure that all vehicles are tested fairly.) NHTSA testing demonstrates it is very difficult to achieve two-wheel lift during CUSC tests without striking cones.

Appearance of Reality = Excellent

In general, double lane change maneuvers have an excellent appearance of reality. The handwheel inputs used by the drivers during Consumers Union Short Course testing emulate the steering a driver might use in an emergency obstacle avoidance maneuver performed on a two-lane road.

13.0 INTERNATIONAL STANDARDS ORGANIZATION (ISO) 3888 PART 2

The International Standards Organization (ISO) 3888 Part 2 Double Lane Change was one of four closed-loop Rollover Resistance maneuvers used in Phase IV[1]. Unlike the Fishhook 1b closed-loop maneuver discussed earlier in this report, this was a driver-based maneuver, i.e., the test driver closed the steering control loop. Since test driver generated steering inputs were used, three drivers were used for the evaluation of each vehicle. This allowed for the determination of the effects of driver variability. The programmable steering machine was not used to generate steering inputs for any ISO 3888 Part 2 tests.

This chapter is comprised of seven sections. Section 13.1 briefly introduces the maneuver with background information. Section 13.2 describes the maneuver and how it was executed. Sections 13.3 and 13.4 discuss the steering and vehicle speed input repeatability, respectively. Section 13.5 discusses output repeatability. Section 13.6 presents test results. Section 13.7 provides a maneuver assessment and concluding remarks.

13.1 ISO 3888 Part 2 Background Information

The ISO 3888 Part 2 Double Lane Change course was developed to observe the way vehicles respond to handwheel inputs drivers might use in an emergency situation. As shown in Figure 13.1, the course requires the driver to make a sudden obstacle avoidance steer to the left, briefly establish position in the left lane, and then rapidly return to the original [right] lane. Use of a second lane, as opposed to a single cone, is the greatest difference between the ISO 3888 Part 2 Double Lane Change course and the Consumers Union Short Course (CUSC). Another difference is that the ISO 3888 Part 2 Double Lane Change sets the widths of the first and second lanes based on the width of the vehicle being evaluated, whereas the CUSC uses the same layout regardless of the test vehicle's dimensions.

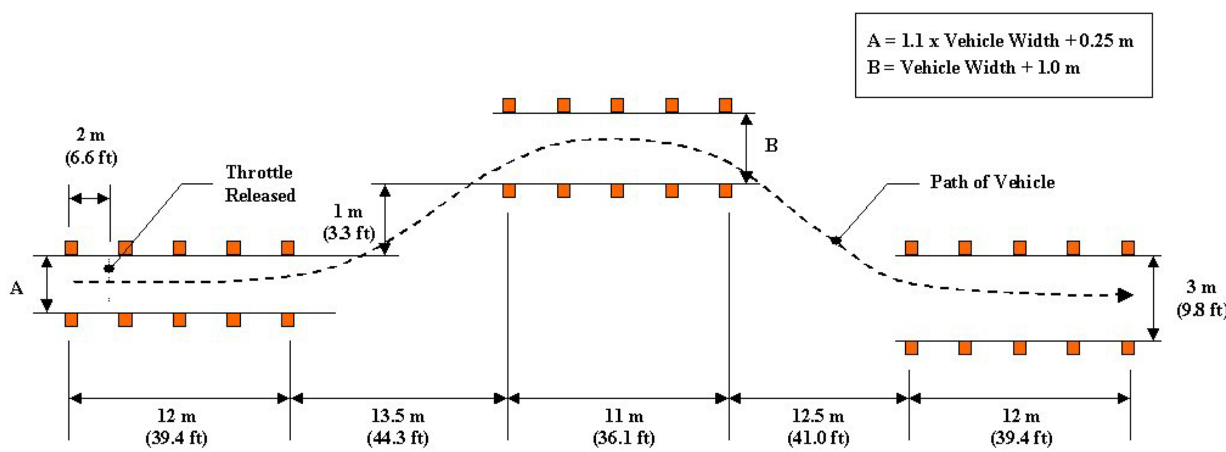

Figure 13.1. ISO 3888 Part 2 double lane change course dimensions.

[1] These maneuvers include the Fishhook 1b, the Path Corrected Limit Lane Change, the ISO 3888 Part 2 Double Lane Change, and the Consumers Union Short Course Double Lane Change.

The ISO 3888 Part 2 course is an improved version of the "Elk Test" used by a Scandinavian automotive magazine (see Figure 13.2). Although the "Elk Test" has resulted in multiple instances of significant two-wheel lift (including the unintentional rollover of a Mercedes A-Class), the course has been criticized because the handwheel steering variability while driving through it can be quite large. The relatively wide lanes of the "Elk Test" allow different drivers, using different steering strategies, to successfully complete the course with the same entrance speed.

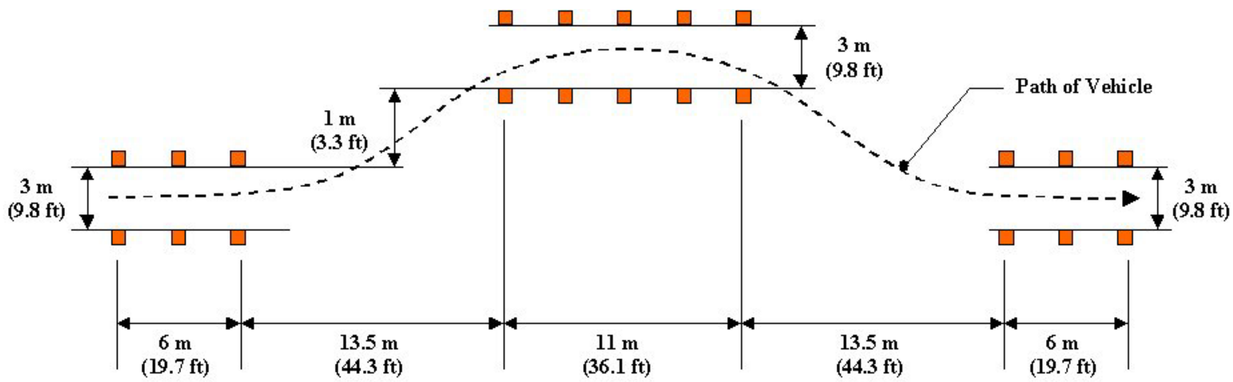

Figure 13.2. "Elk Test" course dimensions.

In an attempt to reduce the handwheel steering variability during tests performed with the "Elk Test" course, the German Alliance of Automotive Industry (VDA) recommended the following modifications:

- Increase the length of the first (entrance) lane from 19.7 to 39.4 ft (6.0 to 12.0 m).
- Set the width of the entrance lane based on the width of the test vehicle. Specifically, the lane width was defined to be the vehicle width multiplied by 1.1 plus 0.8 ft (0.25 m). This generally decreases the width of the entrance lane from the 9.8 ft (3.0 m) dimension used in the "Elk Test."
- Set the width of the second (offset) lane based on the width of the test vehicle. Specifically, the offset lane width was defined to be the vehicle width plus 3.3 ft (1.0 m). This generally decreases the width of the second lane from the 9.8 ft (3.0 m) dimension used in the "Elk Test."
- Decrease the longitudinal distance from the end of the offset lane to the entrance of the third (exit) lane from 44.3 to 41.0 ft (13.5 to 12.5 m).
- Increase the length of the exit lane from 19.7 to 39.4 ft (6.0 to 12.0 m).

Implementation of these recommended changes transformed the “Elk Test” course into the ISO 3888 Part 2 Double Lane Change course shown in Figure 13.1.

13.2 ISO 3888 Part 2 Maneuver Description

To begin this maneuver, the vehicle was driven in a straight line at the desired entrance speed. At a nominal distance of 6.6 ft (2.0 m) after entering the first lane, the driver released the throttle (as shown in Figure 13.1). The maneuver entrance speed was determined when the driver released the throttle. No throttle input or brake application was permitted during the remainder of the maneuver. The driver steered the vehicle from the entrance lane, through the offset (left) lane, then through the exit lane.

Drivers iteratively increased maneuver entrance speed from approximately 35 mph in 1 mph increments. The iterations continued until “clean” tests could no longer be performed (the desired course could not be followed without striking or bypassing cones). Each driver was required to perform three “clean” runs at the their maximum speed. This was to assess input and output variability for tests performed by the same driver, with the same entrance speed.

Runs that were not “clean” were considered to be not valid. The authors support this criterion. If a double lane change were to be used for determining Government dynamic rollover resistance ratings, the authors believe it is essential that the vehicle respect all course delineations.

The manner in which drivers chose to implement the 1 mph iterations was driver-dependent. Some drivers preferred to increase speed until they could no longer achieve a “clean” run. Once this threshold was reached, the driver would reduce speed slightly and perform three “clean” runs. Other drivers would perform three “clean” runs at one speed before proceeding to the next iteration. Both methods produced similar results.

To reduce any confounding effect tire wear may have on ISO 3888 Part 2 Double Lane Change test results, a new tire set was installed on each vehicle, for each driver.

Phase IV ISO 3888 Part 2 Double Lane Change testing was performed using test vehicles in their Nominal Load and Reduced Rollover Resistance configurations.

13.3 ISO 3888 Part 2 Steering Input Variability

The handwheel steering variability associated with ISO 3888 Part 2 Double Lane Change testing was examined in two ways:

1. The variability of the three drivers, considered as a group. This was accomplished by comparing tests performed at the maximum overall “clean” run entrance speed attained by each driver for a particular vehicle. This assessment was therefore based on a total of three tests per vehicle. These tests usually, but not always, included one of the three tests used to evaluate individual driver variability, as explained below.

2. Individual driver variability. For each driver, this assessment was based on the three "clean" tests performed with the fastest but most similar maneuver entrance speeds[2]. This was accomplished by requiring the drivers to perform three tests with nearly equal maneuver entrance speeds. So as to insure maneuver severity would be as great as possible, the drivers were instructed to perform these tests at their maximum attainable "clean" run entrance speed for a given vehicle.

   Individual driver variability analyses were based on a total of nine tests per vehicle, three per driver. Generally speaking, one of the three tests used to assess individual driver variability was also performed at that driver's maximum overall entrance speed. This is explained in greater detail in Section 13.6.3.

13.3.1 Steering Input Variability at the Maximum Overall Entrance Speeds

Tables 13.1 and 13.2 present steering input data collected during ISO 3888 Part 2 tests performed at the maximum overall "clean" entrance speed of each driver in the Nominal Load and Reduced Rollover Resistance configurations, respectively. The ranges of steering angles at each of the three major handwheel peaks are provided along with the corresponding averages and standard deviations. As expected, the variability of these steering angles was much greater than that observed with the steering machine. A substantial range of values was apparent for each of the three major peaks in the steering.

13.3.1.1 Nominal Load

Handwheel steering angles variability was quantified by considering standard deviations of the data (reported as percentages of the mean values in Table 13.1). Generally speaking, steering angles variability increased with each successive input in the Nominal Load configuration. The extent to which these increases occurred depended on the vehicle and peak being considered.

The two exceptions to this trend were the Toyota 4Runner and Mercedes ML320 with enabled stability control. For the 4Runner, the standard deviation of the Initial Steer (22.2 percent) was greater than that of the Reversal #1 or #2 steering (14.1 and 15.6 percent, respectively). When the ML320 was considered, the standard deviation of the Initial Steer (25.0 percent) was greater than that of the Reversal #1 or #2 steering (12.7 and 21.5 percent, respectively

In the Nominal Load configuration, the overall minimum and maximum Initial Steers used by any of the Phase IV vehicles (during tests performed at the maximum "clean" entrance speed attained by the drivers) differed from 35 to 101 degrees. Reversal #1 steering angles differed from 41 to 93 degrees while the Reversal #2 steering varied from 55 to 147 degrees.

[2] The "three "clean" tests performed at the fastest but most similar maneuver entrance speeds" does not necessarily mean the "three fastest overall "clean" entrance speeds." The term "most similar" was quantified by comparing the standard deviations of groups of three maneuver entrance speeds for a particular driver. The group of three "clean" tests whose entrance speeds were each nearest of the maximum attainable "clean" entrance speed of that driver (for a given vehicle) with the lowest standard deviation was defined as the "fastest but most similar."

13.3.1.2 Reduced Rollover Resistance

Handwheel input variability was quantified by considering standard deviations of the data (reported as percentages of the mean values in Table 13.2). Contrary to the trend seen in the Nominal Load configuration, the increase in handwheel input variability with each successive input was only observed for the Ford Escape and Toyota 4Runner with disabled stability control in the Reduced Rollover Resistance configuration. For every other vehicle, the handwheel steering variability of the Initial Steer was greater than that of the Reversal #1 steering. Regardless of which vehicle was considered, the handwheel variability associated with Reversal #2 steering was the greatest in the Reduced Rollover Resistance configuration.

In the Reduced Rollover Resistance configuration, the overall minimum and maximum Initial Steers used by any of the Phase IV vehicles (during tests performed at the maximum “clean” entrance speed attained by the drivers) ranged from 12 to 75 degrees. Reversal #1 steering angles went from 3 to 52 degrees while the Reversal #2 steering varied from 41 to139 degrees.

Table 13.1. Handwheel Angle Peaks During "Clean" ISO 3888 Part 2 Tests Performed at Maximum Maneuver Entrance Speed (Nominal Load).

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)
Toyota 4Runner	Enabled	175 – 266	235	**22.2**	230 – 298	274	**14.1**	180 – 235	199	**15.6**
	Disabled	239 – 275	261	**7.4**	233 – 297	262	**12.2**	144 – 308	214	**39.4**
Chevrolet Blazer	N/A	246 – 309	283	**11.7**	238 – 331	290	**16.3**	211 – 358	268	**29.5**
Ford Escape	N/A	208 – 254	236	**10.5**	206 – 259	229	**11.7**	165 – 237	201	**17.7**
Mercedes ML320	Enabled	161 – 262	226	**25.0**	195 – 248	228	**12.7**	121 – 184	149	**21.5**
	Disabled	231 – 266	248	**7.0**	200 –241	225	**9.6**	181 – 323	230	**34.8**

Table 13.2. Handwheel Angle Peaks During "Clean" ISO 3888 Part 2 Tests Performed at Maximum Maneuver Entrance Speed (Reduced Rollover Resistance).

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)	Range (deg)	Average (deg)	Std Dev (%)
Toyota 4Runner	Enabled	227 – 266	251	**8.3**	230 – 265	249	**7.2**	154 – 243	211	**23.6**
	Disabled	255 – 275	266	**4.0**	227 – 277	255	**10.1**	237 – 376	294	**24.8**
Chevrolet Blazer	N/A	239 – 314	272	**14.1**	248 – 279	264	**5.9**	154 – 252	215	**24.8**
Ford Escape	N/A	238 – 284	263	**8.8**	193 – 245	222	**11.9**	172 – 279	220	**24.8**
Mercedes ML320	Enabled	224 – 247	237	**4.8**	223 – 230	226	**1.5**	147 – 238	195	**23.3**
	Disabled	236 – 248	242	**2.4**	232 – 235	234	**0.7**	187 - 228	204	**10.5**

13.3.2 Steering Input Variability of Individual Drivers

To assess each driver's individual steering input variability, the drivers were required to perform three tests at an entrance speed for which they could just complete the course without striking or bypassing any cones. Figure 13.3 presents nine handwheel inputs (angles and rates) used by the drivers during evaluation of the Ford Escape in the Nominal Load configuration. The variability of these inputs was similar, for each driver, to that observed during tests performed with the other vehicles.

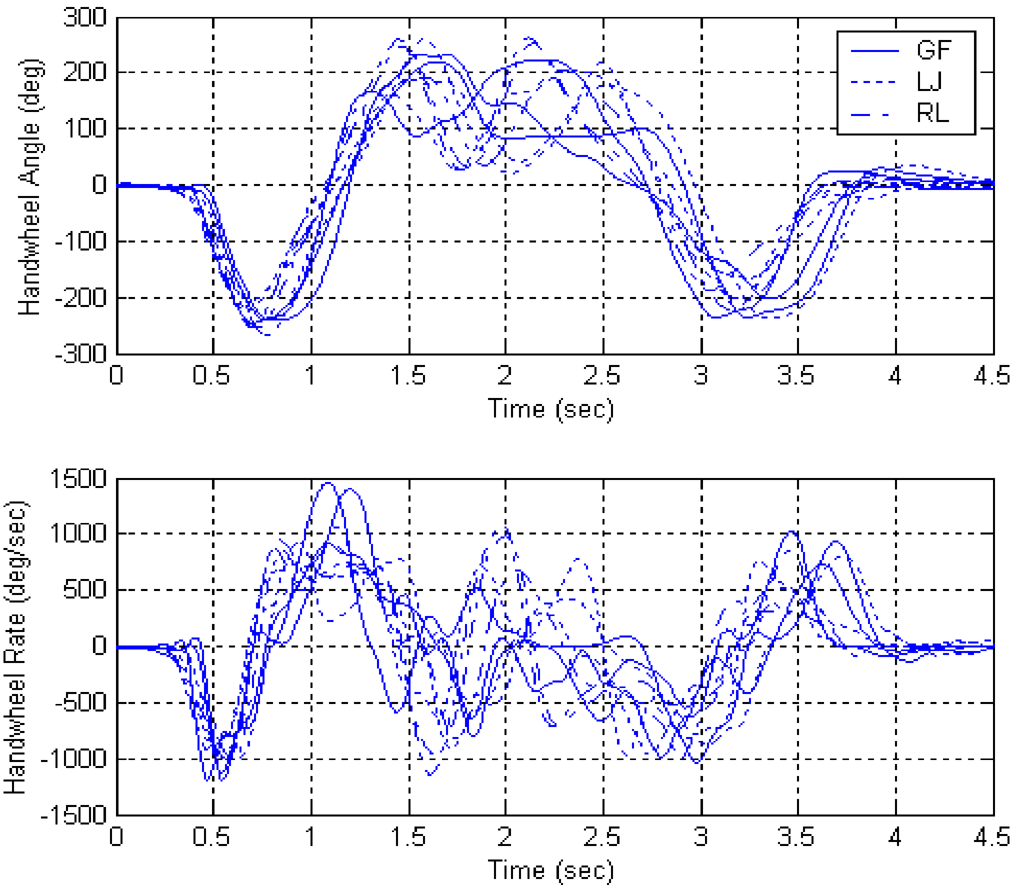

Figure 13.3. Handwheel steering variability of nine "clean" ISO 3888 Part 2 tests performed by three drivers with the Ford Escape in the Nominal Load configuration. (Each set of initials represents a different driver.)

The handwheel data presented in Figure 13.3 were recorded during tests performed at the highest, yet most simlar "clean" maneuver entrance speeds attainable by each driver in the Nominal Load configuration for one vehicle. Figure 13.4 features this data for each Phase IV vehicle, and presents it in a way that more clearly illustrates the range of handwheel angles used by each driver. Each vertical band represents the range of handwheel steering angles produced during tests performed by each driver with their fastest, but most similar, maneuver entrance speeds. The small horizontal lines plotted on each vertical band indicate the average input contained in each range. Figure 13.5 presents similar data collected during tests performed in the Reduced Rollover Resistance configuration.

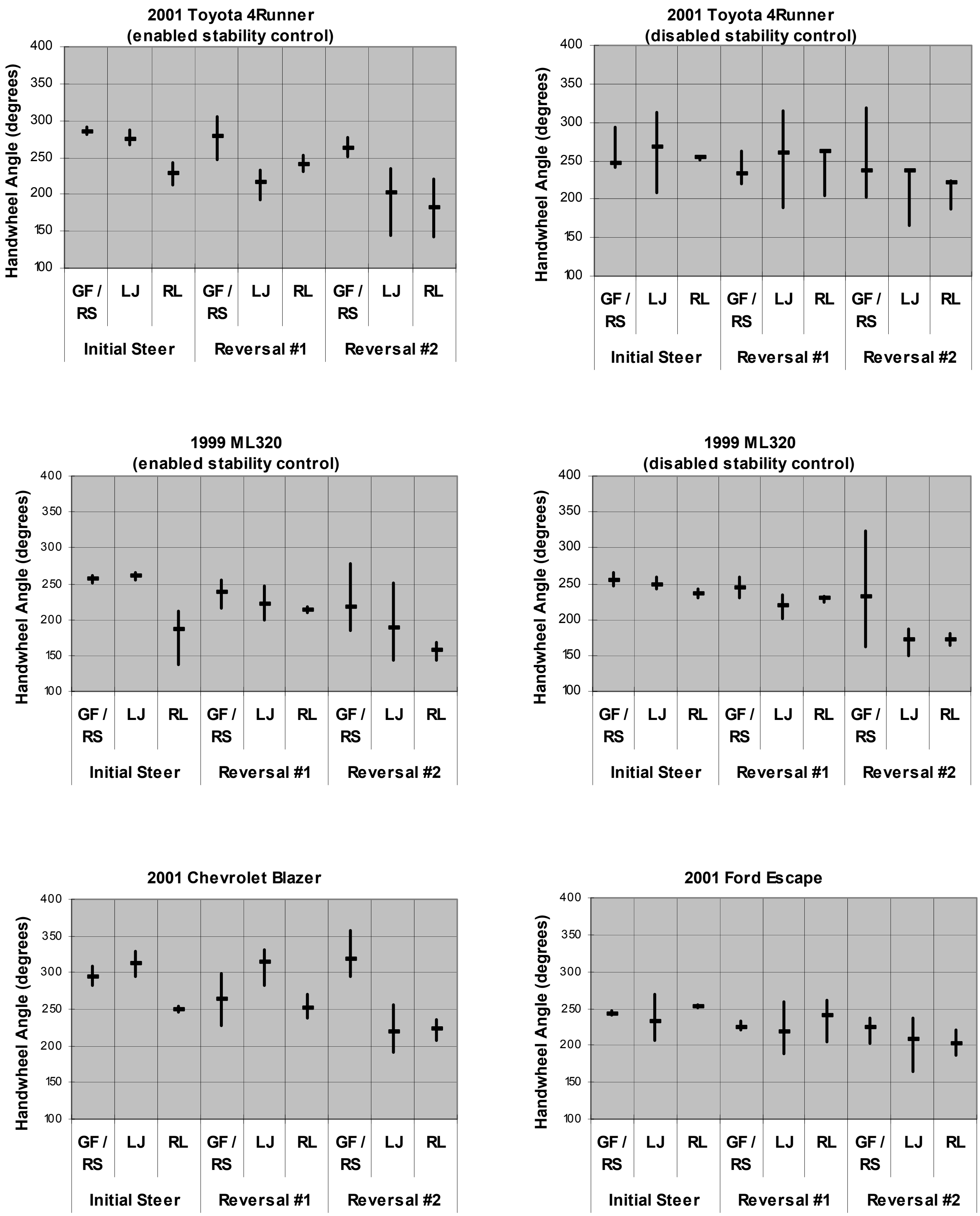

Figure 13.4. Handwheel steering angle variability observed during ISO 3888 Part 2 tests performed in the Nominal Load configuration. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds. (Each set of initials represents a different driver.)

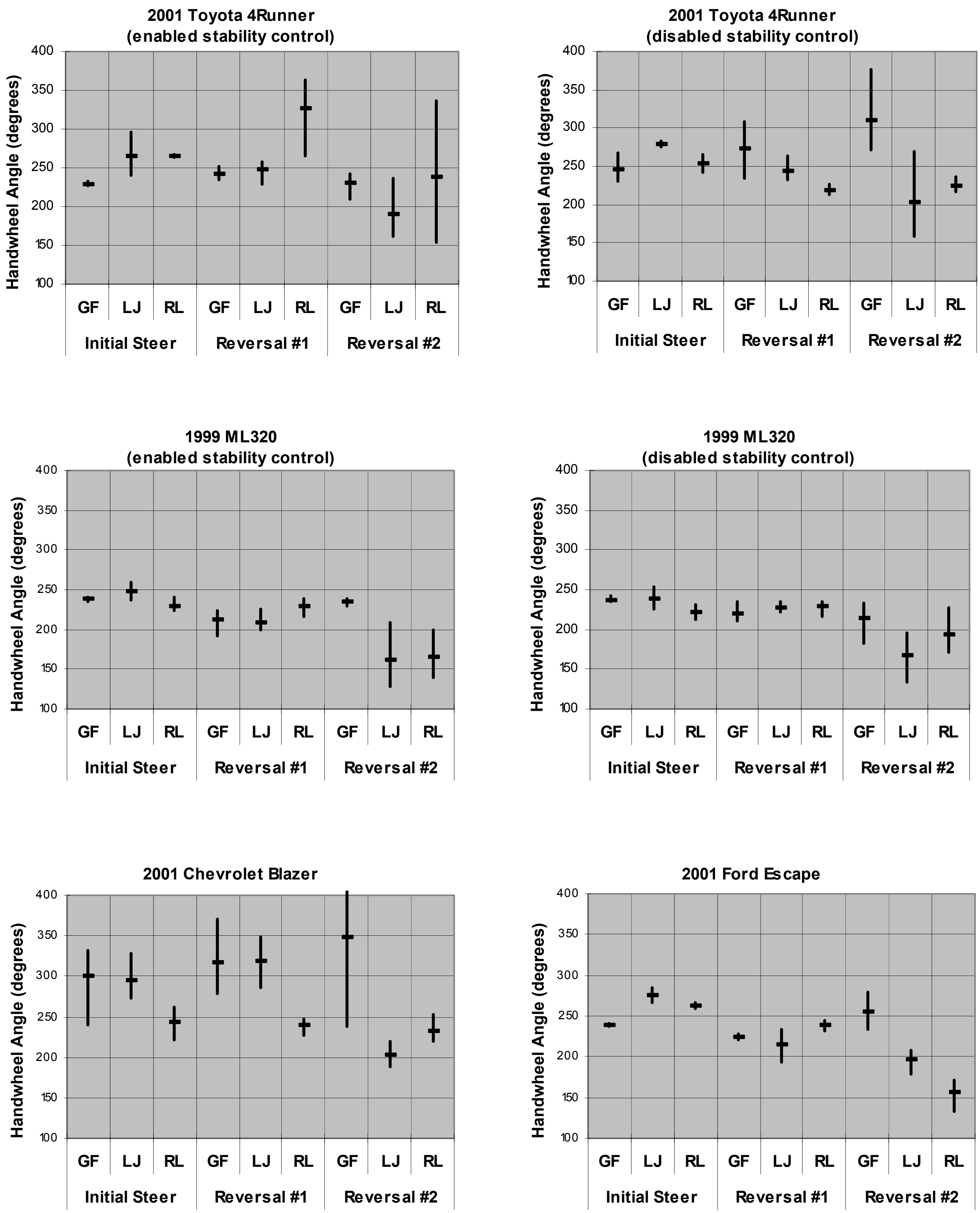

Figure 13.5. Handwheel steering angle variability observed during ISO 3888 Part 2 tests performed in the Reduced Rollover Resistance configuration. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds. (Each set of initials represents a different driver.)

13.3.3 Effect of Stability Control on Steering Input Variability

The Toyota 4Runner and Mercedes ML320 were evaluated with enabled and disabled stability control. As such, it was possible to examine the effect of stability control on the steering input variability of these vehicles using the data presented previously in Tables 13.1 and 13.2. Recall that these data were recorded during tests performed at the overall maximum maneuver “clean” entrance speeds attained by each driver.

13.3.3.1 Nominal Load

When the Toyota 4Runner was tested in the Nominal Load configuration, the overall ranges of Initial Steer and Reversal #1 steering angles were narrower when stability control was disabled. In fact, the entire range of Reversal #1 steering angles with disabled stability control were contained within the respective enabled stability control range.

Two of the three average peak handwheel steering angles during 4Runner testing were larger when stability control was disabled. The average Initial Steer when stability control was disabled was 26 degrees (11.1 percent) greater than that produced with enabled stability control. Conversely, the average Reversal #1 steering angle with disabled stability control was 12 degrees (4.4 percent) *less* that that with it enabled. In agreement with Initial Steer data, the overall average Reversal #2 steering angle with disabled stability control was 15 degrees (7.5 percent) greater than that produced with enabled stability control.

In agreement with 4Runner findings, the overall range of the Initial Steers for the Mercedes ML320 with disabled stability control was less than that with it enabled. Unlike the 4Runner, however, the range of Reversal #1 steering angles was narrower with enabled stability control.

Like the 4Runner, two of the three average peak handwheel steering angles during ML320 testing were larger when stability control was disabled. The average Initial Steer when stability control was disabled was 22 degrees (9.7 percent) greater than that with enabled stability control. Conversely, the average Reversal #1 steering angle with disabled stability control was 3 degrees (1.3 percent) *less* that that with it enabled. In agreement with Initial Steer results, the overall Reversal #2 steering angle with disabled stability control was 81 degrees (54.4 percent) greater than with enabled stability control. The difference between the average peak handwheel steering angles with enabled and disabled stability control at Reversal #2 were much greater than that seen when Initial Steer data were compared for the ML320.

13.3.3.2 Reduced Rollover Resistance

When the Toyota 4Runner was evaluated in the Reduced Rollover Resistance configuration, only the range of Initial Steers was narrower when stability control was disabled.

In agreement with results produced with the 4Runner during tests performed in the Nominal Load configuration, the average Initial Steer and Reversal #2 steering angles were greater when stability control was disabled in the Reduced Rollover Resistance configuration. Unlike the Nominal Load configuration results, however, the average Reversal #1 steering angle was also greater with disabled stability control. The Initial Steer, Reversal #1, and Reversal #2 steering angles recorded during tests performed with disabled stability control were 15, 6, and 83 degrees (6.0, 2.4, and 39.3 percent) greater, respectively, than those when stability control was enabled.

When the Mercedes ML320 was evaluated in the Reduced Rollover Resistance configuration, the range of steering angles was narrower when stability control was disabled for each of the three steering peaks.

In the case of the ML320, the average peak handwheel steering angles were greater when stability control was disabled. That said, the average steering angles for each peak differed by no more than 9 degrees. The Initial Steer, Reversal #1, and Reversal #2 steering angles during tests performed with disabled stability control were 5, 8, and 9 degrees (2.1, 3.5, and 4.6 percent) greater, respectively, than those when stability control was enabled.

13.4 ISO 3888 Part 2 Vehicle Speed Variability

As explained in Section 13.3, each driver performed three "clean" runs at their fastest, but most consistent, maneuver entrance speed for each vehicle. These repetitions permitted vehicle speed repeatability assessment. This assessment included three considerations:

- Ability of the drivers to achieve a desired maneuver entrance speed
- Effect of handwheel steering input variability
- Effect of stability control on vehicle speed, if applicable

13.4.1 Ability of the Drivers to Achieve a Desired Maneuver Entrance Speed

Although the burden placed on the drivers during ISO 3888 Part 2 testing was greater than that imposed by maneuvers using the steering machine, entrance speed repeatability was very good. When all groups of three tests performed at the fastest, most consistent entrance speeds were considered (per driver and vehicle), the greatest speed differentials were 2.0 and 1.3 mph in the Nominal Load and Reduced Rollover Resistance configurations, respectively. This was in agreement with maneuver entrance speed variability observed during other Phase IV Characterization and Dynamic Rollover Propensity maneuvers.

13.4.2 Effect of Handwheel Input Variability

While the approaches just prior to maneuver execution featured good repeatability, the manner in which vehicle speed was scrubbed during the maneuver varied from test-to-test. Steering input variability was largely responsible for this phenomenon.

Figure 13.6 demonstrates how handwheel steering angle variability affected vehicle speed during ISO 3888 Part 2 tests performed with the Chevrolet Blazer in the Nominal Load configuration. To best illustrate this phenomenon, Test 1036 has been highlighted. Of the nine tests presented in Figure 13.6, Test 1036 (performed by driver GF) contains one of the largest Reversal #1 peak steering angles and the largest Reversal #2 peak steering angle. As a result, the exit speed of this test (begun at 39.0 mph) was nearly equal to that of the test begun at the lowest entrance speed shown in Figure 13.6 (37.1 mph).

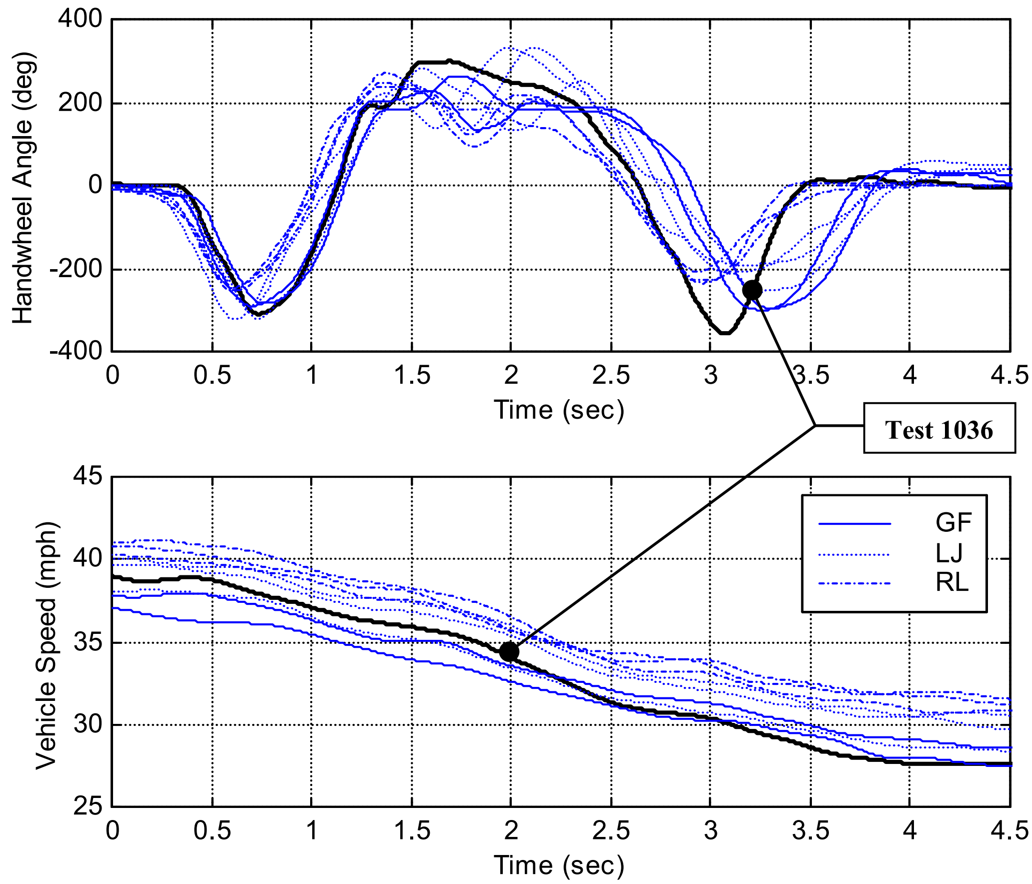

Figure 13.6. Handwheel steering angle and vehicle speed data recorded during ISO 3888 Part 2 tests performed with the Chevrolet Blazer. Note how handwheel steering angle variability affected vehicle speed. (Each set of initials represents a different driver.)

13.4.3 Effect of Stability Control on Vehicle Speed

Like steering input variability, stability control intervention affected the manner in which speed was scrubbed during ISO 3888 Part 2 testing. However, the effect of this intervention was much more pronounced. To quantify the effect of stability control on vehicle speed, the exit speeds of the three "clean" tests performed at the fastest, most consistent entrance speeds with enabled stability control were compared to those with disabled stability control on a per driver basis.

13.4.3.1 Toyota 4Runner

In the case of the 4Runner, the exit speeds of all but one "clean" test performed with enabled stability control were lower than those with disabled stability control, regardless of the vehicle configuration (that said, this trend was especially apparent in the Reduced Rollover Resistance configuration). For the 4Runner, this trend was evident even if the maneuver entrance speeds were slightly higher with enabled stability control.

When results from each of the three drivers in the Nominal Load configuration were considered, the exit speeds of "clean" tests performed with enabled stability control were 7.6 to 11.5 mph (21.3 to 31.9 percent) less than the corresponding maneuver entrance speeds. When stability control was disabled, the exit speeds were 6.0 to 8.2 mph (16.9 to 22.8 percent) less than the corresponding maneuver entrance speeds.

When results from each of the three drivers in Reduced Rollover Resistance configuration were considered, the exit speeds of "clean" tests performed with enabled stability control were 9.1 to 19.1 mph (25.2 to 50.0 percent) less than the corresponding maneuver entrance speeds. When stability control was disabled, the exit speeds were 6.8 to 11.9 mph (18.9 to 31.4 percent) less than the corresponding maneuver entrance speeds.

Figure 13.7 presents handwheel steering angle and vehicle speed data for six "clean" ISO 3888 Part 2 tests performed with the Toyota 4Runner in the Nominal Load configuration. Three of these tests were performed with enabled stability control, and began with entrance speeds of 35.8, 35.4, and 35.7 mph. The tests performed with disabled stability control began at 35.9, 35.4, and 36.1 mph. Driver RL was responsible for all steering inputs presented in Figure 13.7. The vehicle speed variability observed for this driver was representative of that seen for the others.

In this example, the average "clean" maneuver entrance speeds of tests performed with enabled and disabled stability control were nearly equal (35.6 versus 35.8 mph, respectively). However, at the completion of the maneuver[3], the exit speeds with enabled stability control were 7.6 to 9.4 mph (21.3 to 26.5 percent) lower than their respective maneuver entrance speeds. When stability control was disabled, exit speeds were 6.0 to 6.5 mph (16.9 to 18.2 percent) lower than their respective maneuver entrance speeds. At the completion of the maneuver, the average vehicle speed with disabled stability control was 29.6 mph. When stability control was enabled, the average exit speed was 27.2 mph, 8.2 percent lower than that observed when it was disabled.

[3] To provide a basis for comparison, ISO 3888 Part 2 maneuver completion was taken to be 4.5 seconds after the front of the vehicle had reached the timing strip.

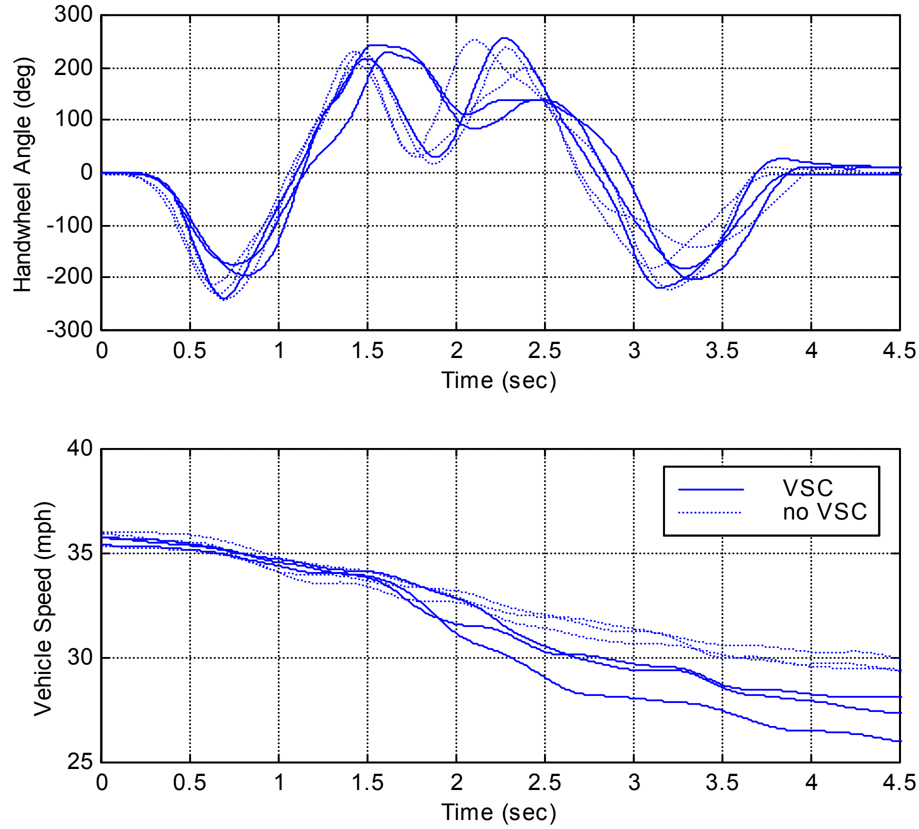

Figure 13.7. Handwheel steering angle and vehicle speed data for six "clean" ISO 3888 Part 2 tests performed with the Toyota 4Runner in the Nominal Load configuration (Driver RL).

13.4.3.2 Mercedes ML320

For the Mercedes ML320, the exit speeds of the three "clean" tests performed at the fastest, most consistent entrance speeds with enabled stability control were quite comparable to those produced with disabled stability control (on a per driver basis). Unlike the 4Runner, the exit speeds of many ML320 tests performed with enabled stability control were nearly equal to those produced with disabled stability control.

When results from each of the three drivers in the Nominal Load configuration were considered, the exit speeds of "clean" tests performed with enabled stability control were 7.6 to 11.7 mph (21.3 to 30.5 percent) less than the corresponding maneuver entrance speeds. When stability control was disabled, the exit speeds were 8.6 to 12.9[4] mph (22.8 to 34.8 percent) less than the corresponding maneuver entrance speeds.

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[4] The test that produced the lowest exit speed for the ML320 with disabled stability control contained a large handwheel reversal after the vehicle had entered the final lane. The magnitude of this reversal was atypical (when compared to any other similar input used during valid tests), and had the effect of scrubbing more speed. Had the driver not steered in this manner, the vehicle would have spun out in the final lane. If results of this test are omitted from the above comparison, the disabled stability control exit speed range is reduced to 8.6 to 9.8 mph (22.8 to 26.6 percent) less than the corresponding maneuver entrance speeds.

When results from each of the three drivers in the Reduced Rollover Resistance configuration were considered, the exit speeds of "clean" tests performed with enabled stability control were 9.0 to 11.2 mph (25.0 to 29.9 percent) less than the corresponding maneuver entrance speeds. When stability control was disabled, the exit speeds were 8.1 to 10.5 mph (22.8 to 29.0 percent) less than the corresponding maneuver entrance speeds.

Figure 13.8 presents handwheel steering angle and vehicle speed data for six "clean" ISO 3888 Part 2 tests performed with the Mercedes ML320 in the Reduced Rollover Resistance configuration. Three of these tests were performed with enabled stability control, and began with entrance speeds of 36.9, 36.0, and 36.6 mph. The tests performed with disabled stability control began at 36.2, 36.3, and 36.0 mph. Driver LJ was responsible for all steering inputs presented in Figure 13.8. The vehicle speed variability observed for this driver was similar to that produced by the others.

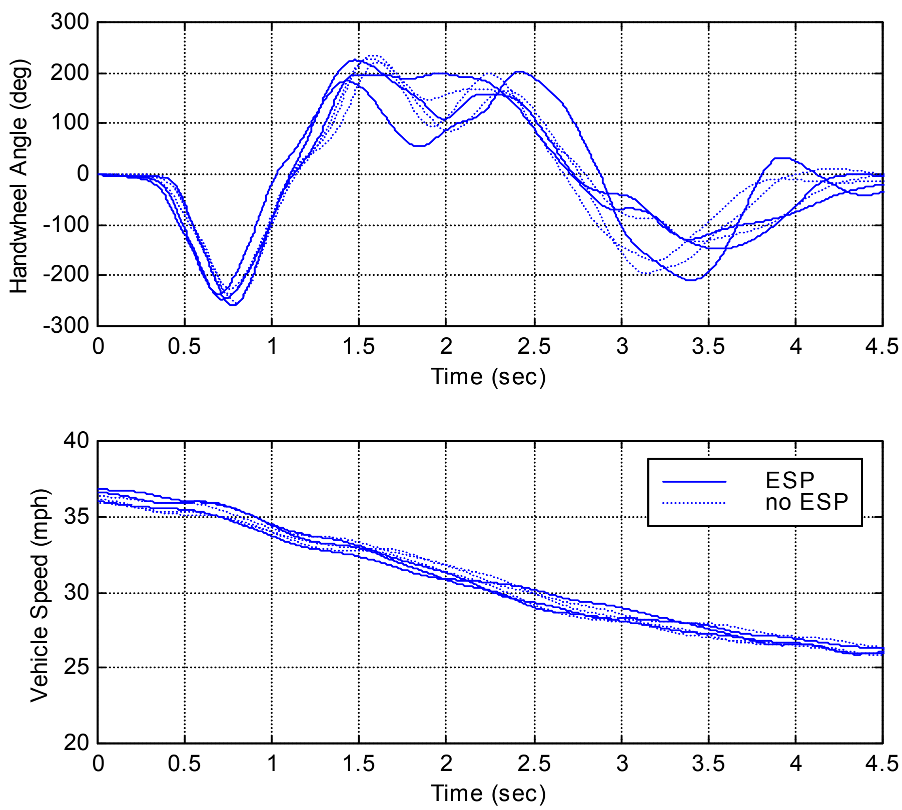


Figure 13.8. Handwheel steering angle and vehicle speed data for six "clean" ISO 3888 Part 2 tests performed with the Mercedes ML320 in the Reduced Rollover Resistance configuration (Driver LJ).

In this example, the average maneuver entrance speeds of tests performed with enabled and disabled stability control were nearly equal (36.3 versus 36.4 mph, respectively). By the completion of the maneuver, for tests with enabled stability control, the vehicle had slowed 10.0 to 10.8 mph (27.8 to 29.4 percent). When stability control was disabled, exit speeds were 9.8 to

10.5 mph (27.2 to 29.0 percent) lower than their respective maneuver entrance speeds. The average exit speed with enabled stability control was 26.1 mph. When stability control was disabled, the average exit speed was 26.0 mph, 0.3 percent lower than when it was enabled.

13.5 ISO 3888 Part 2 Output Variability

In a manner identical to that used to analyze steering input variability, the output variability associated with ISO 3888 Part 2 testing was assessed in two ways:

1. The lateral acceleration variability observed during tests performed at the maximum overall "clean" maneuver entrance speed of each driver, per vehicle.

2. The lateral acceleration variability during tests performed at the three highest, most similar maneuver "clean" entrance speeds performed by individual drivers, per vehicle.

13.5.1 Output Variability of Tests Performed at the Maximum Overall Entrance Speeds

Tables 13.3 and 13.4 present lateral acceleration data collected during ISO 3888 Part 2 tests performed at the maximum overall "clean" entrance speed of each driver in the Nominal Load and Reduced Rollover Resistance load configurations, respectively. The ranges of lateral accelerations at each of the three major handwheel peaks are provided along with the corresponding averages and standard deviations. As expected, the variability of these inputs was much greater than with the steering machine. A substantial range of values was apparent for each of the three major handwheel peaks.

Lateral acceleration variability was quantified by considering standard deviations of the data (reported as percentages of the mean values in Tables 13.3 and 13.4).

Table 13.3. Lateral Acceleration Peaks During "Clean" ISO 3888 Part 2 Tests Performed at Maximum Maneuver Entrance Speed. (Nominal Load)

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)
Toyota 4Runner	Enabled	0.67 – 0.76	0.71	**6.7**	0.70 – 0.73	0.71	**2.4**	0.59 – 0.65	0.62	**5.2**
	Disabled	0.69 – 0.75	0.73	**4.3**	0.73 – 0.77	0.75	**2.6**	0.52 – 0.60	0.57	**7.6**
Chevrolet Blazer	N/A	0.73 – 0.76	0.74	**2.5**	0.78 – 0.84	0.80	**3.6**	0.71 – 0.73	0.72	**0.9**
Ford Escape	N/A	0.71 – 0.78	0.73	**4.9**	0.69 – 0.85	0.76	**10.3**	0.67 – 0.76	0.70	**7.2**
Mercedes ML320	Enabled	0.67 – 0.80	0.74	**8.6**	0.74 – 0.76	0.75	**1.8**	0.48 – 0.55	0.51	**6.8**
	Disabled	0.74 – 0.76	0.75	**1.3**	0.74 – 0.82	0.77	**5.5**	0.70 – 0.72	0.71	**1.3**

Table 13.4. Lateral Acceleration Peaks During "Clean" ISO 3888 Part 2 Tests Performed at Maximum Maneuver Entrance Speed. (Reduced Rollover Resistance)

Vehicle	Stability Control	Initial Steer			Reversal #1			Reversal #2		
		Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)	Range (g)	Average (g)	Std Dev (%)
Toyota 4Runner	Enabled	0.66 – 0.73	0.70	**4.7**	0.69 – 0.75	0.73	**4.8**	0.46 – 0.73	0.59	**22.8**
	Disabled	0.66 – 0.69	0.67	**2.7**	0.81 – 0.83	0.82	**1.8**	0.66 – 0.80	0.73	**9.9**
Chevrolet Blazer	N/A	0.70 – 0.71	0.71	**0.9**	0.74 – 0.80	0.76	**4.3**	0.57 – 0.69	0.64	**9.7**
Ford Escape	N/A	0.68 – 0.72	0.70	**3.4**	0.76 – 0.82	0.79	**3.7**	0.57 – 0.74	0.64	**14.5**
Mercedes ML320	Enabled	0.73	0.73	**0.7**	0.71 – 0.83	0.77	**7.4**	0.53 – 0.73	0.64	**15.9**
	Disabled	0.72 – 0.74	0.73	**1.6**	0.74 – 0.81	0.78	**4.3**	0.62 – 0.71	0.67	**6.8**

13.5.1.1 Nominal Load

Unlike the steering input variability discussed previously, lateral acceleration response variability for the Nominal Load configuration did not increase with each successive steering angle peak.

When stability control was enabled during “clean” tests performed with the Toyota 4Runner and Mercedes ML320, the lateral acceleration variability produced due to the Initial Steer exceeded that due to both of the handwheel steering reversals. When stability control was disabled, the lateral acceleration variability due to the Reversal #1 steering was the largest for the ML320. For the 4Runner with disabled stability control, the maximum lateral acceleration variability occurred due to the Reversal #2 inputs.

For the Chevrolet Blazer and Ford Escape, the lateral acceleration variability was largest due to the Reversal #1 steering.

In the Nominal Load configuration, the range of average lateral accelerations due to the Initial Steer for the Phase IV vehicles was 0.04 g (0.71 to 0.75 g). The range of average lateral accelerations due to the Reversal #1 steering was 0.09 g (0.71 to 0.80 g) while the range due to the Reversal #2 inputs was the largest, 0.21 g (0.51 to 0.72 g).

13.5.1.2 Reduced Rollover Resistance

With one exception, lateral acceleration response variability for the reduced Rollover Resistance configuration increased with each successive handwheel input. For the Toyota 4Runner with disabled stability control, the standard deviation of the lateral accelerations due to the Reversal #1 steering (1.8 percent) was less than that produced due to the Initial Steer or Reversal #2 inputs (2.7 and 9.9 percent, respectively).

In the Reduced Rollover Resistance configuration, the range of average lateral accelerations due to the Initial Steer for the Phase IV vehicles was 0.06 g (0.67 to 0.73 g). The range of average lateral accelerations due to the Reversal #1 steering was 0.09 g (0.73 to 0.82 g) while the range due to the Reversal #2 inputs was the largest, 0.14 g (0.59 to 0.73 g).

13.5.2 Lateral Acceleration Output Variability of the Individual Drivers

ISO 3888 Part 2 Double Lane Change test output variability was assessed by considering lateral acceleration, roll angle, yaw rate, and roll rate responses produced during three “clean” runs performed at the fastest, most consistent maneuver entrance speeds of each driver. Figure 13.9 provides an example of these data. These data were referenced in time to the instant the vehicle reached the course’s timing strip (recall Figure 13.1). The variability of these outputs was similar, for each driver, to that of tests performed with the other vehicles.

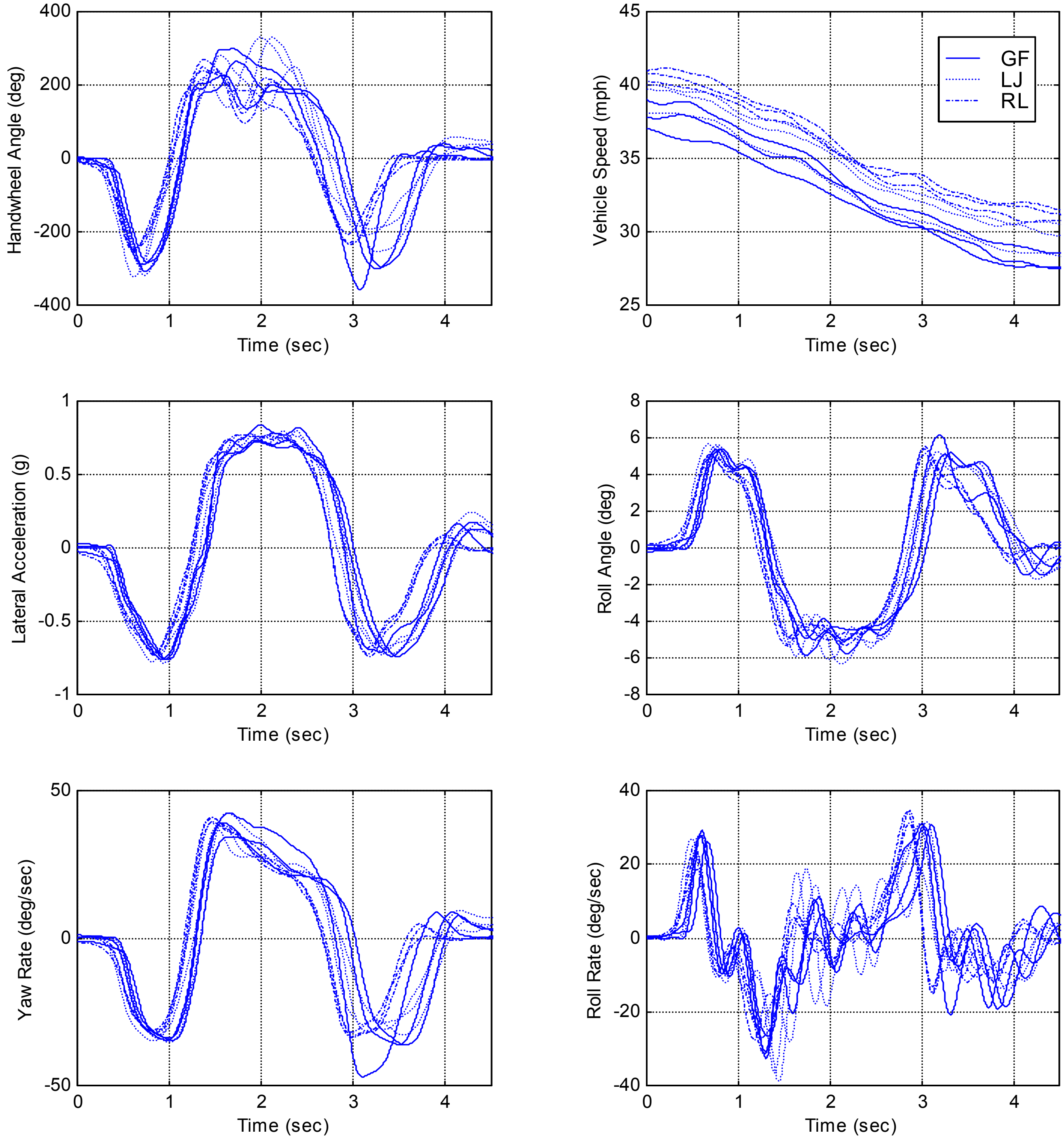


Figure 13.9. Test output repeatability for nine “clean” ISO 3888 Part 2 tests performed with the Chevrolet Blazer in the Nominal Load configuration. (Each set of initials represents a different driver.)

The data presented in Figure 13.9 were recorded during ISO 3888 Part 2 tests performed by the drivers at their highest, yet most consistent, “clean” maneuver entrance speeds in the Nominal Load configuration for one vehicle. Figure 13.10 shows lateral acceleration data for each Phase IV vehicle, and presents it in a way that more clearly illustrates the range of lateral accelerations produced by each driver (when compared to Figure 13.9). Each vertical band represents the range of lateral accelerations produced during tests performed by each driver with their fastest, but most similar, “clean” maneuver entrance speeds. The small horizontal lines plotted on each vertical band indicate the average lateral acceleration contained in each range. Figure 13.11 presents similar data collected during tests performed in the Reduced Rollover Resistance configuration.

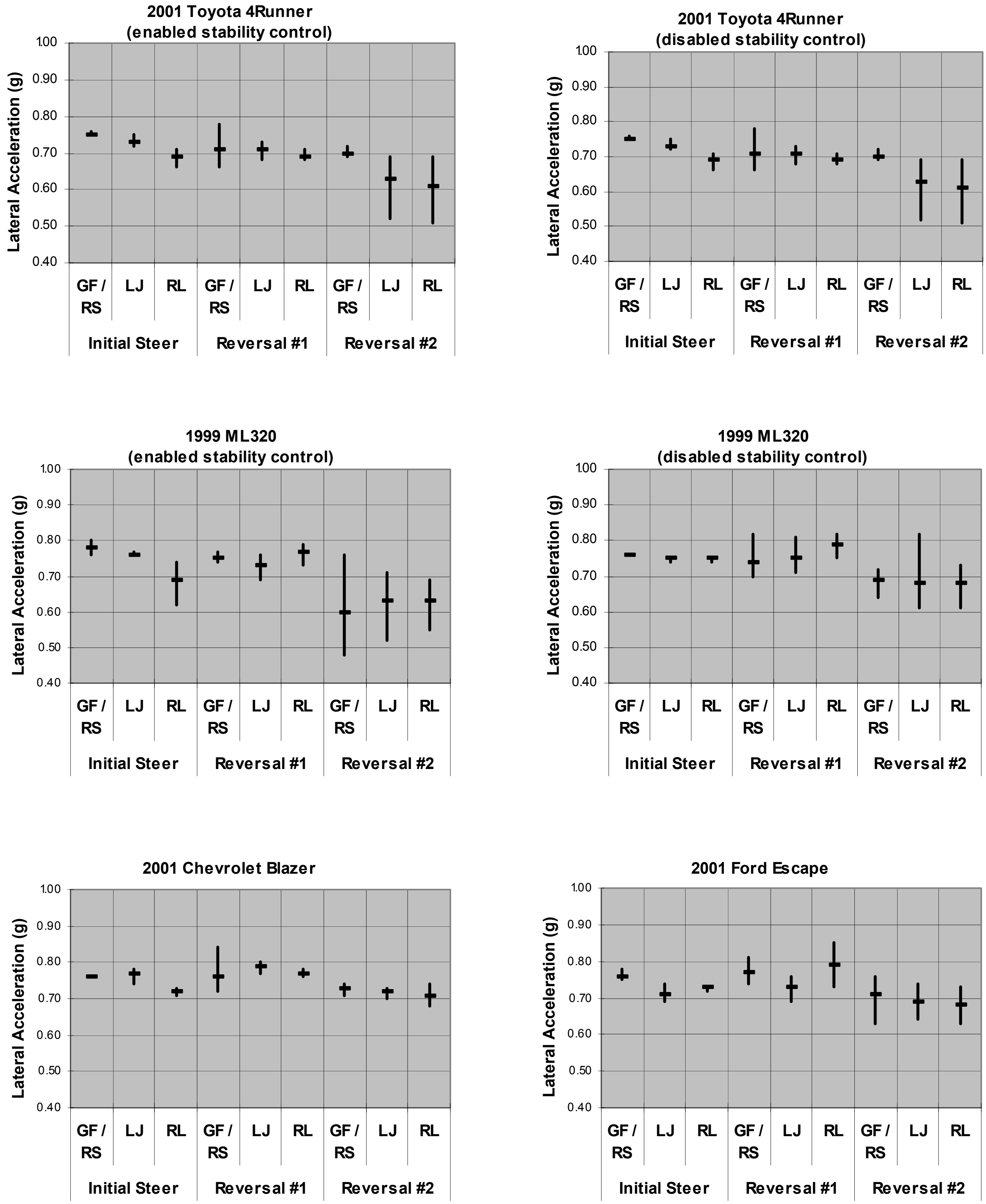


Figure 13.10. Lateral acceleration output variability during ISO 3888 Part 2 testing. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds in the Nominal Load configuration. (Each set of initials represents a different driver).

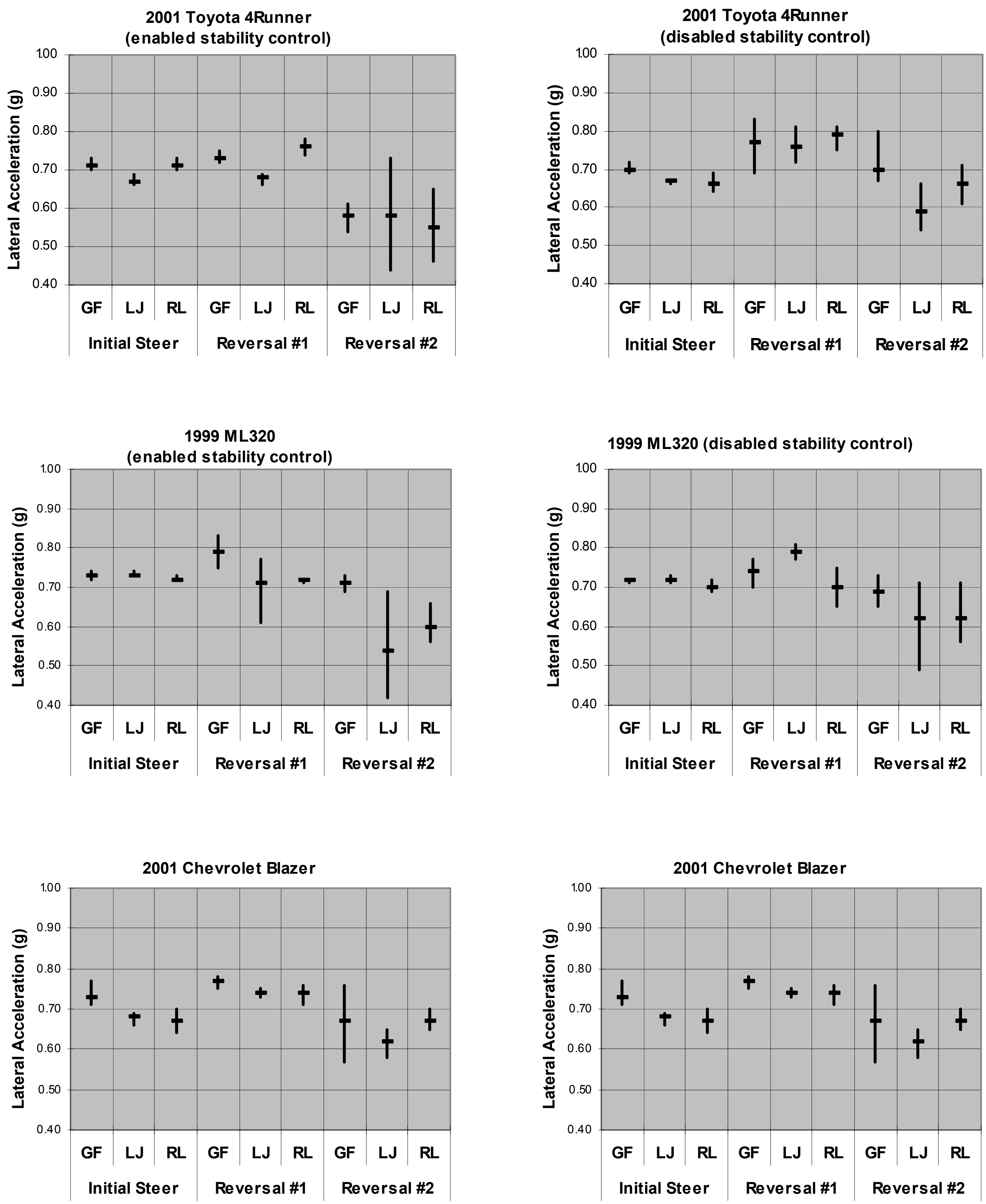


Figure 13.11. Lateral acceleration output variability during ISO 3888 Part 2 testing. Ranges and averages were established with the three "clean" tests performed at the highest, most similar entrance speeds in the Reduced Rollover Resistance configuration. (Each set of initials represents a different driver.)

13.5.3 Effect of Stability Control on Lateral Acceleration Output Variability

The Toyota 4Runner and Mercedes ML320 were evaluated with enabled and disabled stability control. As such, it was possible to examine the effect of stability control on the lateral acceleration output variability of these vehicles using the data presented previously in Tables 13.3 and 13.4. Recall that these data were recorded during tests performed at the overall maximum maneuver entrance speeds attained by each driver.

13.5.3.1 Nominal Load

When the Toyota 4Runner was tested in the Nominal Load configuration, the range of lateral accelerations produced due to the Initial Steer was narrower when stability control was disabled. In fact, this range was contained entirely within that produced due to the Initial Steer during tests performed with enabled stability control. The lateral acceleration variability associated with Reversal #1 and #2 steering, however, was lower with enabled stability control.

In the case of the 4Runner, the average lateral accelerations produced due to the Initial Steer and Reversal #1 steering angles were greatest with disabled stability control. The average lateral acceleration associated with the Initial Steer was 0.02 g (2.8 percent) greater when stability control was disabled, while that associated with Reversal #1 steering was 0.04 g (5.6 percent) greater. Conversely, the average Reversal #2 value with disabled stability control was 0.05 g (8.1 percent) less that that produced when it was enabled.

When the Mercedes ML320 was tested in the Nominal Load configuration, the range of lateral accelerations produced due to the Initial Steer and Reversal #2 steering angles were narrower when stability control was disabled. Like the data produced with the 4Runner, the range of disabled stability control lateral accelerations produced due to the Initial Steer was contained entirely within that produced during tests performed with enabled stability control. The lateral acceleration variability associated with Reversal #1 steering, however, was lower with enabled stability control.

For the ML320, the average lateral accelerations due to each of the major steering angle peaks were greater with disabled stability control. When compared to the average lateral accelerations produced during tests performed with enabled stability control, disabled stability control results were 0.01, 0.02, and 0.20 g (1.4, 2.7, and 39.2 percent) greater, respectively.

13.5.3.2 Reduced Rollover Resistance

When the Toyota 4Runner was tested in the Reduced Rollover Resistance configuration, the lateral acceleration variability associated with each of the three major steering angle peaks was greater when stability control was enabled.

For the 4Runner, the average lateral acceleration associated with the Initial Steer with enabled stability control was 0.03 g (4.3 percent) greater than that produced when it was disabled. The average lateral accelerations produced with Reversal #1 and #2 steering with disabled stability control were 0.09 and 0.14 g (12.3 and 23.7 percent) *greater*, respectively, than those produced when it was enabled.

When the Mercedes ML320 was tested in the Reduced Rollover Resistance configuration, the range of lateral accelerations due to the Initial Steer was narrower when stability control was enabled. Conversely, the range of lateral accelerations due to the Reversal #1 and #2 steering was narrower when stability control was disabled.

For the ML320, the average lateral accelerations produced due to the Initial Steer (0.73 g) were identical, regardless of whether stability control was enabled or disabled. The average lateral accelerations produced due to the Reversal #1 and #2 steering, however, were greater with disabled stability control. When compared to the average lateral accelerations during tests performed with enabled stability control, disabled stability control results were 0.01 and 0.03 g (1.3 and 4.7 percent) greater.

13.6 ISO 3888 Part 2 Results

The severity metric used during this study for ISO 3888 Part 2 testing was maneuver entrance speed. The faster a maneuver entrance speed at which a vehicle is able to complete the course without striking cones or producing two-wheel lift, the better its performance is considered to be. However, this objective metric conflicts with ISO 3888 Part 2. The language accompanying the ISO 3888 Part 2 maneuver description clearly states that test results only "subjectively determine one specific part" of a vehicles overall handling. Specifically, the standard states:

> "Because of the driver influence (driving strategy) in this closed loop test, there is no possibility of an objective measurement of vehicle dynamics data, only subjective evaluation is recommended.
>
> The different paths followed in different tests bring about a considerable scatter in measured velocities. Although longitudinal dynamics are restricted (throttle off 2 m after entering section 1) this does not lead to the desired minimization of the measured velocities. Therefore no ranking in basis of the vehicle velocity and no minimum velocity limit for the vehicles is permitted.
>
> For the reasons given above, the current International Standard defines only the dimensions of the test track for subjective evaluation of vehicle dynamics."

The language of ISO 3888 Part 2 also includes the following statement:

> "Since tests performed on the obstacle avoidance track quantifies only one small part of the complete handling characteristics, the results obtained on this test track can only be considered significant for a correspondingly small part of the overall dynamic behaviour. Therefore, it is not possible to use this International Standard and test results for regulation purposes."

However, since the authors' goal is to develop a dynamic rollover resistance rating system and since the ISO 3888 Part 2 Double Lane Change is being considered for use in this rating system, the authors decided to ignore the above statements.

13.6.1 Overall Maximum Maneuver Entrance Speed

13.6.1.1 Nominal Load

Table 13.5 summarizes the maximum "clean" entrance speeds achieved by each driver during Phase IV ISO 3888 Part 2 Double Lane Change testing performed with vehicles in the Nominal Load configuration.

Overall, the range of maximum maneuver "clean" entrance speeds was quite narrow (i.e., when all of the Phase IV vehicles were considered together). The highest maximum "clean" entrance speed for any driver, for test vehicles evaluated in the Nominal Load configuration, was 41.0 mph. Driver RL achieved this speed during tests performed with the Chevrolet Blazer. The lowest maximum "clean" entrance speed was 35.3 mph, for Driver LJ during Toyota 4Runner testing with disabled stability control. The difference between the slowest and fastest overall maximum "clean" entrance speeds was only 5.7 mph (16.1.

Table 13.5. Maximum Maneuver Entrance Speeds Achieved by Each Driver During "Clean" ISO 3888 Part 2 Tests. (Nominal Load)

Driver	Toyota 4Runner		Chevrolet Blazer (mph)	Ford Escape (mph)	Mercedes ML320	
	VSC (mph)	No VSC (mph)			ESP (mph)	No ESP (mph)
GF / RS	37.6[1]	36.0[1]	39.0	36.9	38.0[1]	37.2[1]
LJ	36.7	35.3	40.0	36.6	37.0	36.7
RL	35.8	37.0	41.0	38.0	36.8	37.8
Average	36.7	36.1	40.0	37.2	37.3	37.2
Std Dev	0.9	0.9	1.0	0.7	0.6	0.6
Min - Max	**1.8**	**1.7**	**2.0**	**1.4**	**1.2**	**1.1**

[1]Tests performed by Driver RS.

When stability control was enabled, the maximum "clean" entrance speeds of the Toyota 4Runner in the Nominal Load configuration ranged from 35.8 to 37.6 mph, differing by up to 1.8 mph (5.0 percent). When stability control was disabled, the range of "clean" entrance speeds (35.3 to 37.0 mph) was similar, differing by up to 1.7 mph (4.8 percent).

The maximum maneuver "clean" entrance speeds of the Chevrolet Blazer in the Nominal Load configuration ranged from 39.0 to 41.0 mph, differing by up to 2.0 mph (5.1 percent).

The range of speeds observed for the Ford Escape in the Nominal Load configuration was 36.6 to 38.0 mph. The maximum "clean" entrance speeds differed by up to 1.4 mph (3.8 percent).

When stability control was enabled, the maximum "clean" entrance speeds of the Mercedes ML320 in the Nominal Load configuration ranged from 36.8 to 38.0 mph, differing by up to 1.2 mph (3.3 percent). When stability control was disabled the range of "clean" entrance speeds (36.7 to 37.8 mph) was similar, differing by up to 1.1 mph (3.0 percent).

13.6.1.2 Reduced Rollover Resistance

Table 13.6 summarizes the maximum "clean" entrance speeds achieved by each driver during Phase IV ISO 3888 Part 2 Double Lane Change testing performed with vehicles in the Reduced Rollover Resistance configuration. In agreement with results obtained in the Nominal Load configuration, Drivers LJ and RL attained their highest "clean" entrance speeds with the Chevrolet Blazer during tests performed in the Reduced Rollover Resistance configuration. However, the highest "clean" entrance speed for Driver GF was achieved with the Toyota 4Runner with enabled stability control.

Table 13.6. Maximum Maneuver Entrance Speeds Achieved by Each Driver During "Clean" ISO 3888 Part 2 Tests. (Reduced Rollover Resistance)

Driver	Toyota 4Runner		Chevrolet Blazer (mph)	Ford Escape (mph)	Mercedes ML320	
	VSC (mph)	No VSC (mph)			ESP (mph)	No ESP (mph)
GF	39.3	38.0	36.8	37.3	37.4	36.1
LJ	36.8	37.2	38.0	36.5	36.9	36.3
RL	38.5	37.4	39.0	35.6	36.5	37.1
Average	38.2	37.5	37.9	36.5	36.9	36.5
Std Dev	1.3	0.4	1.1	0.9	0.5	0.5
Min - Max	**2.5**	**0.8**	**2.2**	**1.7**	**0.9**	**1.0**

The maximum achievable "clean" entrance speed of the Toyota 4Runner with enabled stability control **increased** to 39.3 mph in the Reduced Rollover configuration from 37.6 mph in the Nominal Load configuration. This increase of 2.7 mph is 7.2 percent of the lower speed. The average "clean" entrance speed for the three drivers **increased** by 1.5 mph (4.1 percent) to 38.2 mph in the Reduced Rollover configuration from 36.7 mph in the Nominal Load configuration.

The maximum achievable "clean" entrance speed of the Toyota 4Runner with disabled stability control **increased** to 38.0 mph in the Reduced Rollover configuration from 37.0 mph in the Nominal Load configuration. This increase of 1.0 mph is 2.7 percent of the lower speed. The average "clean" entrance speed **increased** by 1.4 mph (3.9 percent) to 37.5 mph in the Reduced Rollover configuration from 36.1 mph in the Nominal Load configuration.

The maximum achievable “clean” entrance speed of the Chevrolet Blazer decreased to 39.0 mph in the Reduced Rollover configuration from 41.0 mph in the Nominal Load configuration. This decrease of 2.0 mph is 5.1 percent of the lower speed. The average “clean” entrance speed decreased by 2.1 mph (5.5 percent) to 37.9 mph in the Reduced Rollover configuration from 40.0 mph in the Nominal Load configuration.

The maximum achievable “clean” entrance speed of the Ford Escape decreased to 37.3 mph in the Reduced Rollover configuration from 38.0 mph in the Nominal Load configuration. This decrease of 0.7 mph is 1.9 percent of the lower speed. The average “clean” entrance speed also decreased by 0.7 mph (1.9 percent) to 36.5 mph in the Reduced Rollover configuration from 37.2 mph in the Nominal Load configuration.

The maximum achievable “clean” entrance speed of the Mercedes ML320 with enabled stability control decreased to 37.4 mph in the Reduced Rollover configuration from 38.0 mph in the Nominal Load configuration. This decrease of 0.6 mph is 1.6 percent of the lower speed. The average “clean” entrance speed decreased by 0.4 mph (1.1 percent) to 36.9 mph in the Reduced Rollover configuration from 37.2 mph in the Nominal Load configuration.

The maximum achievable “clean” entrance speed of the Mercedes ML320 with disabled stability control decreased to 37.1 mph in the Reduced Rollover configuration from 37.8 mph in the Nominal Load configuration. This decrease of 0.7 mph is 1.9 percent of the lower speed. The average “clean” entrance speed also decreased by 0.7 mph (1.9 percent) to 36.5 mph in the Reduced Rollover configuration from 37.2 mph in the Nominal Load configuration.

Overall, the range of maximum maneuver “clean” entrance speeds was quite narrow (i.e., when all of the Phase IV vehicles were considered together). The highest maximum “clean” entrance speed for any driver, for any vehicle evaluated in the Reduced Rollover Resistance configuration, was 39.3 mph. Driver GF achieved this speed during tests performed with the Toyota 4Runner with enabled stability control. The lowest maximum “clean” entrance speed was 35.6 mph, for Driver RL with the Ford Escape. The difference between the slowest and fastest overall maximum “clean” entrance speeds was only 3.7 mph (10.4 percent of the lower speed)

When tested in the Reduced Rollover Resistance configuration with enabled stability control, the maximum “clean” entrance speeds for the Toyota 4Runner ranged from 36.8 to 39.3 mph, differing by up to 2.5 mph (6.8 percent). This range was greater than that produced during tests performed with Nominal loading. When stability control was disabled, the range of “clean” entrance speeds (37.2 to 38.0 mph) differed by a lesser extent, up to 0.8 mph (2.2 percent). This range was less than that produced during similar tests performed in the Nominal Load configuration.

The maximum “clean” entrance speeds for the Chevrolet Blazer ranged from 36.8 to 39.0 mph in the Reduced Rollover Resistance configuration, differing by up to 2.2 mph (6.0 percent). This range was slightly greater than that produced during similar tests performed in the Nominal Load configuration.

The range of “clean” entrance speeds for the Ford Escape was 35.6 to 37.3 mph in the Reduced Rollover Resistance configuration. The maximum “clean” entrance speeds differed by up to 1.7 mph (4.8 percent). This range was slightly greater than that produced during similar tests performed in the Nominal Load configuration.

When stability control was enabled, the maximum “clean” entrance speeds for the Mercedes ML320 ranged from 36.5 to 37.4 mph in the Reduced Rollover Resistance configuration, differing by up to 0.9 mph (2.5 percent). This range was half of that produced during similar tests performed in the Nominal Load configuration. When stability control was disabled, the range of “clean” entrance speeds (36.1 to 37.1 mph) differed to a greater extent, up to 1.0 mph (2.8 percent). Once again, this range was less than that produced during similar tests performed in the Nominal Load configuration.

13.6.2 Effect of Stability Control on Overall Maximum Entrance Speed

13.6.2.1 Nominal Load

With two exceptions, the drivers were able to achieve their highest maneuver “clean” entrance speeds with enabled stability control, if the vehicle was so equipped. Driver RL was able to achieve a higher maneuver “clean” entrance speed with disabled stability control during testing of the Toyota 4Runner and Mercedes ML320. However, all differences between maximum maneuver “clean” entrance speeds with enabled and disabled stability control were small, differing by no more than 1.6 mph.

For the 4Runner, the maximum “clean” entrance speeds with enabled stability control of tests performed by Drivers RS and LJ were 1.6 and 1.4 mph (4.4 and 4.0 percent) greater, respectively, than those achieved with disabled stability control. However, Driver RL was able to achieve a 1.2 mph (3.4 percent) greater maximum maneuver “clean” entrance speed with disabled stability control.

For the Mercedes ML320, the maximum “clean” entrance speeds with enabled stability control of tests performed by Drivers RS and LJ were 0.8 and 0.3 mph (2.2 and 0.8 percent) greater, respectively, than those achieved with disabled stability control. However, Driver RL was able to achieve a 1.0 mph (2.7 percent) greater maximum maneuver “clean” entrance speed with disabled stability control.

13.6.2.2 Reduced Rollover Resistance

With two exceptions, the drivers were able to achieve their highest maneuver “clean” entrance speeds with enabled stability control, if the vehicle was so equipped. Driver LJ was able to achieve a higher maneuver “clean” entrance speed with disabled stability control during evaluation of the Toyota 4Runner. Similarly, Driver RL was able to achieve a higher maneuver “clean” entrance speed with disabled stability control during evaluation of the Mercedes ML320. However, all differences between maximum maneuver “clean” entrance speeds with enabled and disabled stability control were small, differing by no more than 1.3 mph in the Reduced Rollover Resistance configuration.

For the 4Runner, the maximum "clean" entrance speeds with stability control enabled of the tests performed by Drivers GF and RL were 1.3 and 1.1 mph (3.4 and 2.9 percent) greater, respectively, than those achieved with disabled stability control. However, Driver LJ was able to achieve a 0.4 mph (1.1 percent) greater maximum maneuver "clean" entrance speed with disabled stability control.

For the Mercedes ML320, the maximum "clean" entrance speeds with enabled stability control of tests performed by Drivers GF and LJ were 1.3 and 0.6 mph (3.6 and 1.7 percent) greater, respectively, than those achieved with disabled stability control. However, Driver RL was able to achieve a 0.6 mph (1.6 percent) greater maximum maneuver "clean" entrance speed with disabled stability control.

13.6.3 Comparison of Maximum and Average Maneuver Entrance Speeds

Tables 13.7 and 13.8 compare each driver's maximum overall entrance speed for a particular vehicle to the average of the three highest, most consistent maneuver entrance speeds achieved by that driver for the Nominal Load and Reduced Rollover Resistance configurations, respectively. If the maximum entrance speed of a driver related well to the average speed of the highest, most consistent maneuver entrance speeds, it is likely the full potential of that driver was realized during ISO 3888 Part 2 testing.

13.6.3.1 Nominal Load

Regardless of the vehicle or driver being considered, the average speeds presented in Table 13.7 were each within 1.2 mph (3.4 percent) of the maximum maneuver "clean" entrance speeds. The fact these differences were low was not surprising, given that the three tests performed at the highest, most consistent "clean" entrance speeds generally contained the test performed at the maximum overall "clean" entrance speed. There were only three exceptions to this. During tests performed with the Toyota 4Runner (with enabled stability control by Driver LJ, with it disabled by Drivers RL and RS), the maximum "clean" entrance speeds achieved by the respective drivers were greater than each of the three highest, most consistent maneuver "clean" entrance speeds.

13.6.3.2 Reduced Rollover Resistance

Regardless of the vehicle or driver being considered, the average speeds presented in Table 13.8 were each within 1.4 mph (3.8 percent) of the maximum maneuver "clean" entrance speeds. Once again, the fact these differences were low was not surprising, given that the three tests performed at the highest, most consistent "clean" entrance speeds generally contained the test performed at the maximum overall "clean" entrance speed. There were only two exceptions to this. During tests performed with the Chevrolet Blazer by Driver LJ and with the Mercedes ML320 with disabled stability control by Driver RL, the maximum "clean" entrance speeds achieved by the respective drivers were greater than each of the three highest, most consistent maneuver "clean" entrance speeds.

13.6.4 Two-Wheel Lift

No two-wheel lift occurred during any "clean" run.

The only instance of two-wheel lift produced during ISO 3888 Part 2 testing occurred when Driver GF attempted to perform the maneuver at high speed. When this driver entered the course at 38.7 mph with the Toyota 4Runner with disabled stability control, the vehicle began to spinout after Reversal #2. While spinning, the vehicle began to oscillate in roll and produced two-wheel lift. Due to the spinout, three cones in the exit lane were hit, and the vehicle departed the course to the left. It is very important to recognize this test was not valid. Although the speed was less than that used by this driver in the Nominal Load configuration, it was performed at a speed for which successful completion of the course was unlikely (about 0.7 mph greater than the highest speed attained by any driver for the 4Runner in the Reduced Rollover Resistance configuration with disabled stability control. The test is mentioned only to demonstrate that two-wheel lift was only realized during a non-valid test using the ISO 3888 Part 2 Double Lane Change course.

13.6.5 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact were observed during ISO 3888 Part 2 testing, regardless of vehicle, driver, or vehicle configuration.

Table 13.7. Comparison of Average vs. Maximum Maneuver Entrance Speeds for ISO 3888 Part 2 Tests (Nominal Load).

Driver	Toyota 4Runner, VSC (mph)			Toyota 4Runner, no VSC (mph)			Chevrolet Blazer (mph)			Ford Escape (mph)			Mercedes ML320, ESP (mph)			Mercedes ML320, no ESP (mph)		
	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase
GF / RS	37.2[1]	37.6[1]	**1.1**[1]	35.3[1]	36.0[1]	**2.0**[1]	38.0	39.0	**2.6**	36.4	36.9	**1.4**	37.8[1]	38.0[1]	**0.5**[1]	36.1[1]	37.2[1]	**3.1**[1]
LJ	36.1	36.7	**1.7**	35.2	35.3	**0.3**	39.3	40.0	**1.8**	35.8	36.6	**2.2**	36.3	37.0	**1.9**	36.4	36.7	**0.8**
RL	35.6	35.8	**0.6**	35.8	37.0	**3.4**	40.7	41.0	**0.7**	37.8	38.0	**0.5**	35.6	36.8	**3.4**	37.5	37.8	**0.8**

[1]Tests performed by Driver RS.

Table 13.8. Comparison of Average vs. Maximum Maneuver Entrance Speeds for ISO 3888 Part 2 Tests (Reduced Rollover Resistance).

Driver	Toyota 4Runner, VSC (mph)			Toyota 4Runner, no VSC (mph)			Chevrolet Blazer (mph)			Ford Escape (mph)			Mercedes ML320, ESP (mph)			Mercedes ML320, no ESP (mph)		
	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase	Ave	Max	% Increase
GF	38.8	39.3	**1.3**	37.6	38.0	**1.1**	36.6	36.8	**0.5**	36.9	37.3	**1.1**	37.1	37.4	**0.8**	35.9	36.1	**0.6**
LJ	36.4	36.8	**1.1**	36.6	37.2	**1.6**	36.6	38.0	**3.8**	36.1	36.5	**1.1**	36.5	36.9	**1.1**	36.2	36.3	**0.3**
RL	38.2	38.5	**0.8**	37.1	37.4	**0.8**	38.7	39.0	**0.8**	35.3	35.6	**0.8**	36.1	36.5	**1.1**	36.0	37.1	**3.1**

13.7 ISO 3888 Part 2 Maneuver Assessment

Using the criteria presented in Chapter 2, the authors have rated ISO 3888 Part 2 testing in the following manner:

Objectivity and Repeatability = Bad

Since the test driver generates steering inputs for the ISO 3888 Part 2 Double Lane Change maneuver, vehicle performance in this maneuver depends upon the skill of the test driver, the steering strategy used by the test driver, plus random run-to-run fluctuations. Unlike the Consumers Union Short Course, the ISO 3888 Part 2 layout maneuver attempts to minimize this variability by using three cone-delineated lanes, rather than two lanes and a gate, and by relating the width of two of the three lanes to test vehicle width. These course layout differences endeavor to minimize the number of paths available to the driver while maintaining a high maneuver severity level.

Despite these attempts to minimize variability, as Tables 13.1 and 13.2 and Figures 13.3 through 13.5 demonstrate, both substantial driver-to-driver differences and substantial within driver run-to-run differences in the steering inputs occurred during the Phase IV ISO 3888 Part 2 testing. These differences tended to increase as the maneuver progressed. That said, these differences might not necessarily matter for the purposes of determining Rollover Resistance Ratings. What really matters are driver-to-driver and run-to-run differences in vehicle outputs, specifically how they influence the vehicle rating metric.

As suggested by the DaimlerChrysler Corporation, the rating metric used by NHTSA was the maximum maneuver entrance speed for which a driver successfully achieved a "clean" run (i.e., none of the cones delineating the course were struck or bypassed). Using three test drivers, the overall range of maximum maneuver "clean" entrance speeds in the Nominal Load configuration varied from 1.1 mph for the Mercedes ML320 with disabled stability control, to 2.0 mph for the Chevrolet Blazer. The average range was 1.5 mph. While these may seem like small ranges, the entire range of maximum attainable maneuver "clean" entrance speeds was only 5.7 mph when all of the Phase IV vehicles were considered. Since the Phase IV vehicles are believed to be representative of typical, current generation sport utility vehicles, these results imply the maximum valid maneuver "clean" entrance speeds achievable for most sport utility vehicles will fall within this 5.7 mph range. Therefore, driver-to-driver variability accounts for an average of 27 percent of the rating metric's range. The range of maximum maneuver "clean" entrance speeds of the Chevrolet Blazer suggests that this variability can account for up to 35 percent of the rating metric range.

Table 13.9 presents a rank ordering of the Phase IV rollover test vehicles based on the maximum "clean" entrance speeds achieved by the three test drivers. Note that "1" is the best rank and "6" the worst. This table clearly shows the problem caused by driver-to-driver variability combined with the small range of metric values. While the Chevrolet Blazer attained the best ranking from all three drivers, the rankings for the Ford Escape, Mercedes ML320 with stability control enabled, and the Toyota 4Runner with stability control enabled varied by three places (e.g., 2nd to 5th).

Table 13.9. Vehicle Rankings Based on Maximum Entrance Speeds for "Clean" ISO 3888 Part 2 Tests Performed in the Nominal Vehicle Configuration.

Driver	Chevrolet Blazer	Ford Escape	Mercedes ML320 (ESP)	Mercedes ML320 (no ESP)	Toyota 4Runner (VSC)	Toyota 4Runner (no VSC)
GF/RS	1	5	2[1]	4[1]	3[1]	6[1]
LJ	1	5	2	3	3	6
RL	1	2	5	3	6	4

[1]Tests performed by Driver RS.

Driver skills and abilities vary with time. Although this was not directly measured in Phase IV, the authors believe that if the ISO 3888 Part 2 course was used to re-test the Phase IV vehicles, with the same drivers, the results would not be exactly reproduced. Since the rating metric range established in Phase IV was so narrow, day-to-day (or even hour-to-hour) changes in test driver performance could potentially change the maximum maneuver "clean" entrance speeds by a substantial percentage of the overall range.

Due to the problems associated with driver-to-driver variability and run-to-run (for the same driver) variability, the Objectivity and Repeatability of the ISO 3888 Part 2 Double Lane Change maneuver was rated as bad.

Performability = Good

The procedure for performing tests with the ISO 3888 Part 2 course was straightforward. However, as discussed above, use of this course is associated with objectivity and repeatability issues. Resolving these issues will add difficulty and complexity to the test procedure.

For example, one possibility for improving objectivity and repeatability is to use multiple drivers to perform the testing (three drivers were used during the NHTSA testing). While this should help, there are still potential problems. One exceptionally skilled test driver could generate very good performance metrics for a mediocre vehicle. If this exceptionally skilled driver did not test some other vehicle, that vehicle's performance metrics might, incorrectly, be lower than they should be. Therefore, in addition to using multiple drivers, procedures would need to be developed to ensure that drivers of approximately equal skill test every vehicle.

For the Government's purpose, the authors believe a test maneuver should adapt to differing vehicle characteristics so as to maximize severity. In the case of a double lane change, the course layout must be modified on a per-vehicle basis so as to achieve worst-case lane geometry. The ISO 3888 Part 2 Double Lane Change layout adjusts to the vehicle being tested. However, based on the fact two-wheel lift was not detected during any ISO 3888 Part 2 test for which no course delimiting cones were struck, the authors to not believe the layout imposes the worst-case lane geometry for any of the Phase IV vehicles. For this reason, the Performability rating of tests using the ISO 3888 Part 2 course was only slightly greater than assigned to Consumers Union Short Course testing.

Discriminatory Capability = Very Bad

ISO 3888 Part 2 tests were performed with each vehicle in the Nominal Load and Reduced Rollover Resistance configurations. Despite the use of high steering magnitudes and production of high lateral accelerations, no two-wheel lift occurred during any "clean" run performed using the ISO 3888 Part 2 course, for any of the Phase IV test vehicles. While one two-wheel lift did occur during a run that was not "clean", this should not be considered for the determination of our rollover resistance ratings. The reason is that when a run is not "clean", the path-following nature of the test is no longer meaningful. The driver could use an infinite combination of steering inputs. For example, rather than attempting to perform a "clean" run, the driver could input the fishhook steering required to produce two-wheel lift. To achieve a high maneuver entrance speed, the driver could simply drive straight through the course without any avoidance steering. Either case would simply be recorded as a "not clean" test, although the test outcomes are obviously very different.

Unlike the J-Turn and Fishhook maneuvers, the occurrence/non-occurrence of two-wheel lift cannot be used as a measure of vehicle performance for this maneuver because two-wheel lifts during "clean" runs are unlikely to occur. The rating metric used by NHTSA therefore was the maximum entry speed into the test course at which a driver successfully achieved a "clean" run.

When tested in the Reduced Rollover Resistance configuration, vehicles had ballast placed on their roofs so as to raise their center of gravity heights. Addition of the roof-mounted ballast reduced the Static Stability Factors of these vehicles by approximately 0.05. A 0.05 reduction in SSF equates, for sport utility vehicles, to approximately a one star reduction in the vehicle's rollover resistance rating. As was previously stated, NHTSA believes that a one star reduction in the rollover resistance rating should make a vehicle substantially easier to rollover. Maneuvers with good discriminatory capability should measure substantially worse performance when the Reduced Rollover Resistance configuration is imposed on a test vehicle (when compared with performance observed in the Nominal Load configuration).

Table 13.10 presents the maximum achievable "clean" entrance speeds attained by any of the test drivers for both the Nominal Vehicle and Reduced Rollover Resistance configuration for each of the Phase IV rollover test vehicles. When results from the two load configurations were compared, a substantial change in rollover resistance was not seen. While the maximum achievable "clean" entrance speeds attained by each test driver in the Reduced Rollover Resistance configuration did decrease slightly when compared to comparable Nominal Load results for three vehicles, they increased slightly for the 2001 Toyota 4Runner.

When each of the vehicles was considered, the overall the average difference in maneuver entrance speed was 0.4 mph. The average of the absolute values of these differences was 1.3 mph. It is important to recognize both average differences are less than the average driver-to-driver variability of 1.5 mph.

Table 13.10. Maximum Entrance Speeds Achieved by Each Driver During "Clean" ISO 3888 Part 2 Tests. Nominal Vehicle and Reduced Rollover Resistance Configurations are Compared.

Load Configuration	Chevrolet Blazer (mph)	Ford Escape (mph)	Mercedes ML320; ESP (mph)	Mercedes ML320; no ESP (mph)	Toyota 4Runner; VSC (mph)	Toyota 4Runner; no VSC (mph)
Nominal Load	41.0	38.0	38.0	38.9	37.6	37.0
Reduced Rollover Resistance	39.0	37.3	37.4	37.1	39.3	38.0
Difference	2.0	0.7	0.6	1.8	-1.7	-1.0

The expected substantial change in expected rollover resistance measurement was not observed for the ISO3888 Part 2 Double Lane Change maneuver apparently because the sensitivity of the test to handling properties is predominant compared to its sensitivity to rollover resistance. Placing weight on a vehicle's roof raises its center of gravity height, which reduces its rollover resistance. However, doing this also increases a vehicle's mass and roll moment of inertia, resulting in changes to a vehicle's handling that are not well understood. Since handling and rollover resistance are inextricably intertwined in the rating produced by this maneuver, the rating generated can improve even though the rollover resistance of a vehicle is getting worse.

Results from both J-Turn and Fishhook testing are, of course, also influenced by the handling characteristics of the vehicle. However, handling has less of a chance to dominate these maneuvers because they involve fewer major steering movements (one for a J-Turn, two for a Fishhook, and three for a Double Lane Change).

The above reasoning also explains an apparent anomaly in Table 13.9. In this table, the Chevrolet Blazer has the best ranking of any of the vehicles. However, based on its one star rating and performance in the NHTSA J-Turn and Fishhooks, we believe it to have the lowest rollover resistance of any of the Phase IV rollover test vehicles. The apparent contradiction is resolved once we realize that the ISO3888 Part 2 Double Lane Change maneuver measures mostly the handling rather than rollover resistance of vehicles.

Since tests using the ISO 3888 Part 2 Double Lane Change Course measure some combination of vehicle handling and rollover resistance (with handling characteristics apparently dominating the measured metric values), the authors can rate the Discriminatory Capability of the ISO 3888 Part 2 Double Lane Change maneuver for rollover resistance (not emergency handling) as no better than very bad.

Appearance of Reality = Excellent

In general, double lane change maneuvers have excellent appearance of reality. The handwheel inputs used by the drivers during ISO 3888 Part 2 testing emulate the steering a driver might use in an emergency obstacle avoidance maneuver performed on a two-lane road.

14.0 OPEN-LOOP PSEUDO DOUBLE LANE CHANGES

Closed-loop, path-following double lane changes have historically been associated with considerable handwheel variability. This was in evidence during ISO 3888 Part 2 and Consumers Union Short Course tests performed as part of the Phase IV research. Although the ISO 3888 Part 2 course layout attempts to minimize this shortcoming by relating lane width to vehicle width, handwheel variability observed during this maneuver continues to greatly exceed that typically occurring during steering machine-based maneuvers.

Aside from the handwheel variability issues, double lane changes have a certain appeal. The inputs of either of the above mentioned double lane changes could emulate a driver's reaction to a variety of crash avoidance scenarios. Furthermore, examination of what effects the third steering input (second reversal) has on dynamic rollover propensity is of interest. To examine third steer effects without the confounding effect of handwheel variability, open-loop handwheel inputs generated by the steering machine were used to approximate double lane changes.

Two open-loop double lane changes were performed in Phase IV: ISO 3888 Part 2 and Consumers Union Short Course simulations. For each maneuver, handwheel inputs were chosen to approximate those observed during closed-loop, path-following tests performed at VRTC by three test drivers. Specifically, steering recorded during the three "clean" tests begun with the highest, yet most similar, entrance speeds was considered for each driver, per maneuver. Using these data, handwheel input composites were developed. The subsequent maneuvers were named "Open-Loop *Pseudo* Double Lane Changes because the maneuvers were not intended to be path-following in nature; the inputs are fixed on a per vehicle basis for each test condition. Open-loop pseudo double lane changes were performed in only the Nominal Load configuration, with the Toyota 4Runner and Chevrolet Blazer. The Ford Escape and Mercedes ML320 were not evaluated with these maneuvers.

This chapter is comprised of seven sections. Section 14.1 describes the maneuver and how it was executed. Section 14.2 and 14.3 discuss the steering and vehicle speed input repeatability, respectively. Section 14.4 discusses maneuver entrance speed variability. Section 14.5 discusses output repeatability. Section 14.6 presents test results. Section 14.7 provides a maneuver assessment and concluding remarks.

14.1 Open-Loop Pseudo Double Lane Change Maneuver Description

14.1.1 Handwheel Inputs

Upon completion of the path-following double lane changes, the three highest, most consistent maneuver "clean" run entrance speeds (see Chapters 12 and 13 for definition) attained by each driver were determined. (A "clean" run was one in which no cones were struck or bypassed.) This produced a total of nine runs for each vehicle (recall that the 4Runner with enabled stability control was considered to be separate vehicle from the 4Runner with disabled stability control).

Double lane change simulation began by plotting the handwheel angles for all drivers of a particular vehicle. The plots were overlaid and centered about the middle peak of the maneuver in the time domain. Figure 14.1 demonstrates this technique by displaying the handwheel inputs observed during the Consumers Union Short Course (CUSC) testing with the Toyota 4Runner with enabled stability control.

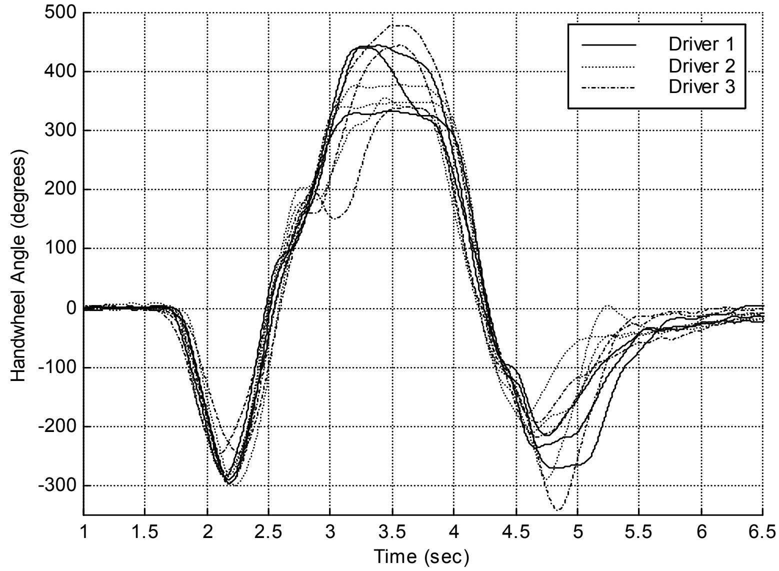


Figure 14.1. Handwheel angles observed during nine "clean" CUSC tests performed with the Toyota 4Runner with enabled stability control.

After each of the nine tests was centered, the data were averaged to form a preliminary composite. Figure 14.2 displays the preliminary composite and the nine tests used to define it (previously shown in Figure 14.1).

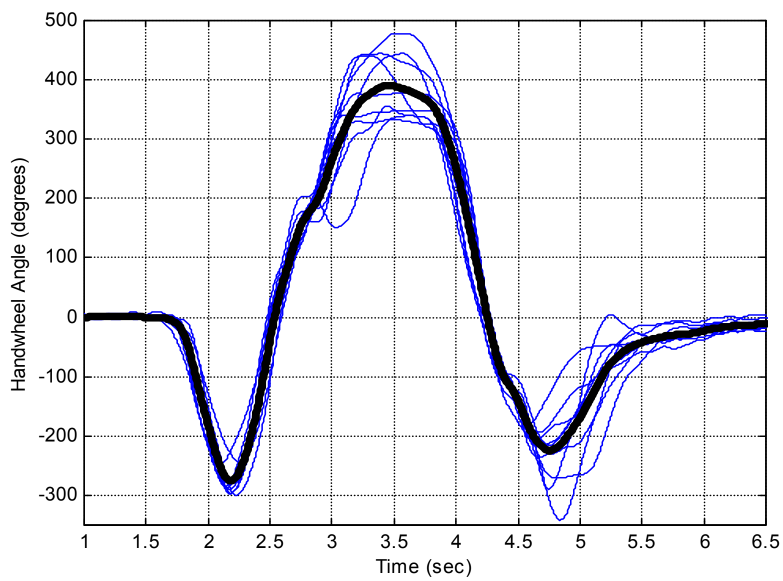


Figure 14.2. Comparison of the preliminary CUSC handwheel composite and the nine inputs used to develop it (Toyota 4Runner with enabled stability control).

Once the preliminary composite was created, averages for each of the three primary handwheel peaks were calculated. These averages were based on peak value data (independent of time) from each of the nine closed-loop tests. Each average was then divided by the appropriate preliminary composite value to produce a ratio. The three ratios were averaged to produce a final, overall ratio. This final ratio was multiplied by preliminary composite data to yield a final handwheel input composite[1]. In the previously presented 4Runner example, the final composite peaks were three percent greater than comparable preliminary composite values.

Piecewise approximation was used to construct ramp-based handwheel profiles representative of the final handwheel composites. The approximation was programmed into the steering machine, and the maneuver performed. Figure 14.3 presents a comparison of the preliminary composite, the final composite, and the piecewise approximation for the previously presented data.

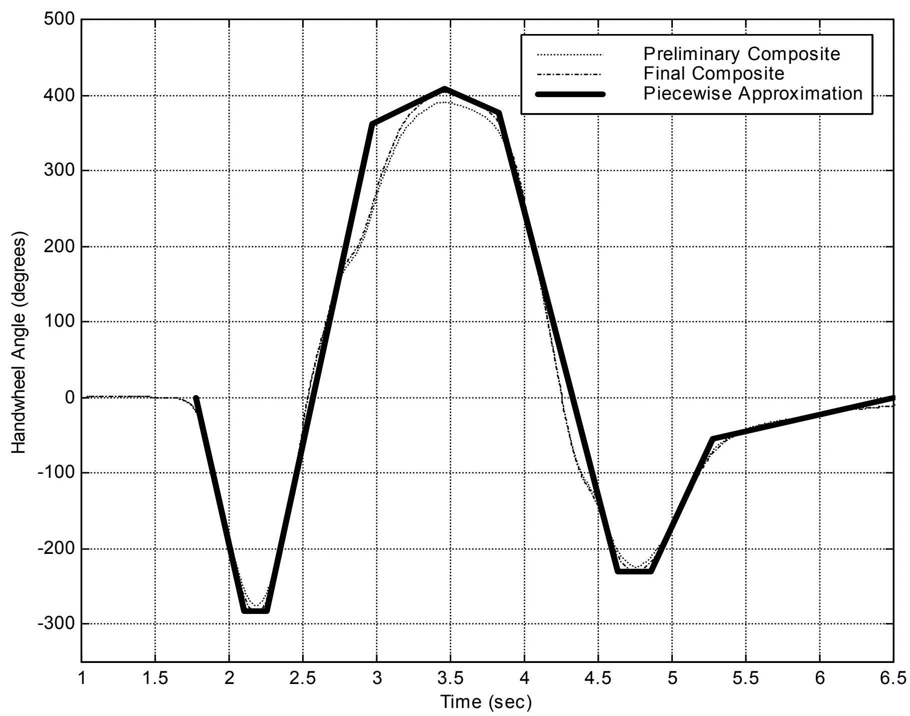


Figure 14.3. Comparison of preliminary and final CUSC handwheel composites and the CUSC piecewise approximation (Toyota 4Runner with enabled stability control).

Figure 14.4 presents the suite of piecewise approximations used for the CUSC simulations for the Toyota 4Runner with both enabled and disabled stability control and Chevrolet Blazer. The two 4Runner approximations were in generally good agreement, but significant differences were

[1] Determination of the final composite was necessary because the peak handwheel input of a particular test did not necessarily occur at the same time as the others. The preliminary composite was used to establish trends (e.g., timing, rates, etc.) in the handwheel position data. The final composite increased handwheel magnitudes, so as to insure maneuver severity was preserved.

apparent at the onset and completion of the maneuver. At the onset, the two 4Runner inputs differed because the piecewise approximation of the disabled stability control input included a shallow (16 degree), 285 ms duration handwheel ramp just prior to the “primary” first steer input. Inclusion of this ramp allowed the approximation to more accurately represent the handwheel inputs used by the test drivers during previously discussed path-following tests.

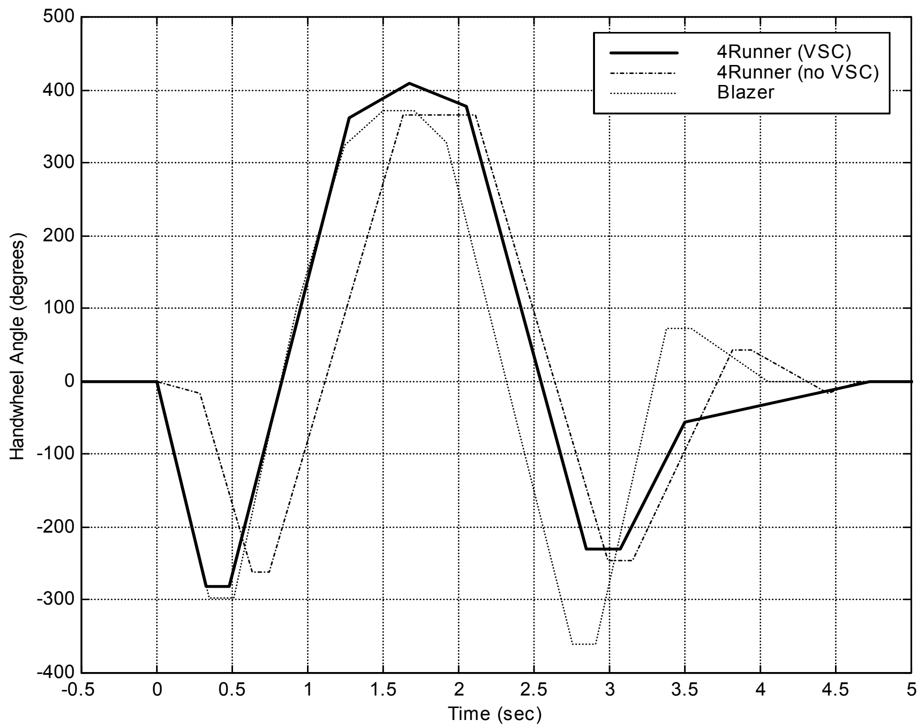


Figure 14.4. CUSC piecewise approximations for thee test vehicles.

Generally speaking, closed-loop CUSC tests performed with the Blazer and 4Runner with disabled stability control contained four or five significant steering inputs (i.e., three or four reversals). The drivers used the fifth steering input to preserve lateral stability and achieve desired exit lane position for the 4Runner with disabled stability control and for the Blazer. This fifth input was not present in the piecewise approximation of 4Runner with enabled stability control steering.

Due to the length of the second lane in the ISO 3888 Part 2 course, each driver was required to make steering adjustments after the second handwheel peak to maintain lane position. As a result, each ISO 3888 Part 2 simulation contained five significant handwheel peaks. Figure 14.5 presents a comparison of the piecewise approximations used for each vehicle. Unlike the CUSC simulation, the inclusion of a corrective counter steering near maneuver completion was not required for ISO 3888 Part 2 approximations, regardless of vehicle or stability control status.

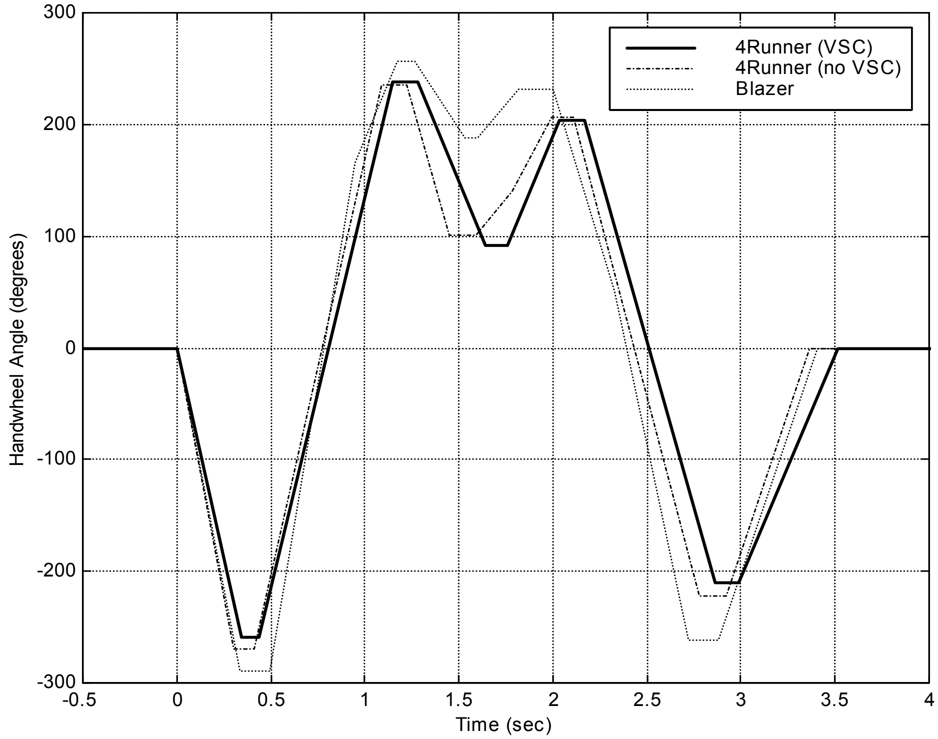


Figure 14.5. ISO 3888 Part 2 piecewise approximations for three test vehicles.

14.1.2 Test Conduct

The ISO 3888 Part 2 and CUSC simulations were performed as open-loop maneuvers. No driver steering input was used. As was the case for all of the Phase IV testing, the driver controlled the throttle. These tests were exploratory in nature, and only performed with two test vehicles. Vehicle speed began at 35 mph and was iteratively increased in 5 mph increments to 50 mph or until two-wheel lift occurred. Additionally, tests were performed at the average maximum entrance speed attained by test drivers at VRTC during closed-loop tests not using the steering machine (see Chapter 12 and 13).

Open-loop pseudo double lane changes were not intended to be path-following tests. Rather, they were performed to investigate how two steering reversals can affect rollover propensity and lateral stability without the confounding effects of steering variability.

14.2 Open-Loop Pseudo Double Lane Change Steering Input Repeatability

The handwheel magnitudes used to define open-loop pseudo double lane changes were driver and vehicle dependent, based on the inputs used by three drivers at their three highest, most consistent maneuver entrance speeds. For each vehicle, data were collected during ISO 3888 Part 2 and CUSC path-following tests were considered separately. Using these data and the techniques described above, a piecewise linear desired handwheel input was developed for each vehicle/maneuver combination. Since the handwheel input remained the same for all runs for a given vehicle/maneuver combination, entrance speed was used as a maneuver severity metric. A number of speed iterations were made for each vehicle/maneuver combination before a termination condition was realized.

Because the handwheel inputs remained constant throughout this iterative process, an assessment of steering repeatability was possible. Figures 14.6 and 14.7 present these data for the Toyota 4Runner for the ISO 3888 Part 2 and CUSC open-loop pseudo double lane changes, respectively. Five tests per maneuver are shown. All tests were performed in the Nominal Load configuration with stability control. The excellent repeatability of the handwheel inputs makes it nearly impossible to distinguish the individual tests from each other, however some disparity was observed near completion of the second handwheel ramps of both maneuvers.

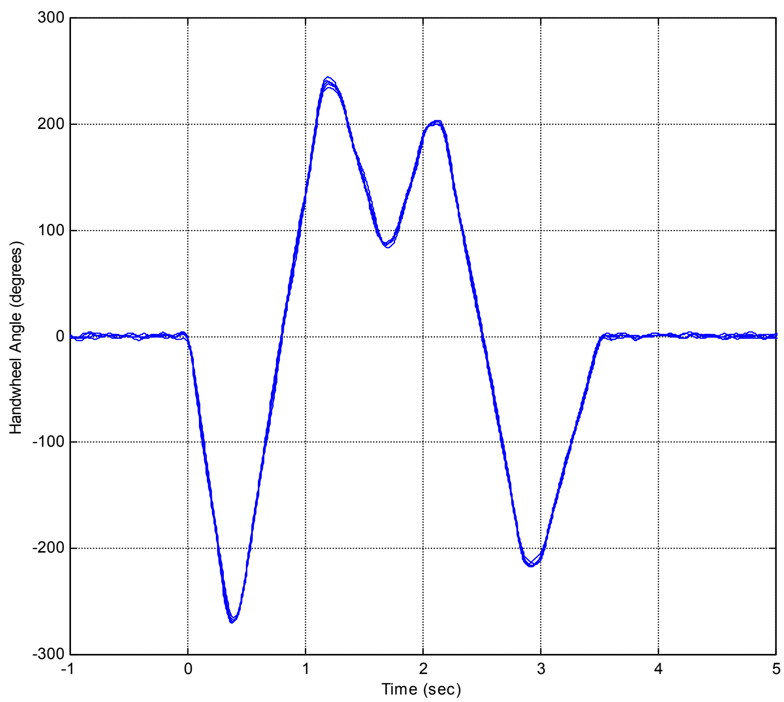


Figure 14.6. Handwheel angles recorded during five Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes performed with the Toyota 4Runner with enabled stability control.

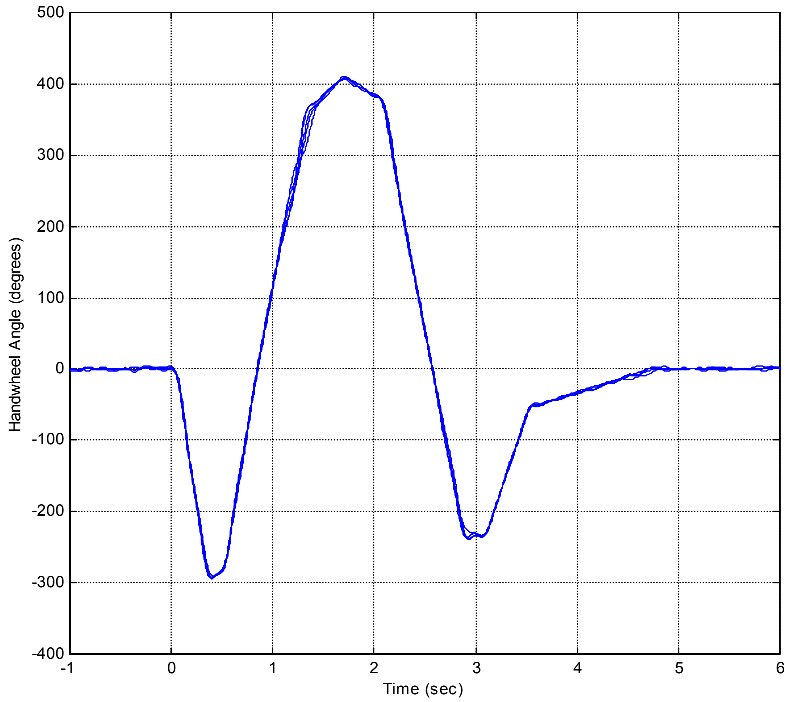


Figure 14.7. Handwheel angles recorded during five Open-Loop Pseudo CUSC Double Lane Changes performed with the Toyota 4Runner with enabled stability control.

14.3 Open-Loop Pseudo Double Lane Change Vehicle Speed Repeatability

Figure 14.8 presents handwheel position and vehicle speed data for three Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes performed with the Toyota 4Runner. Two of these tests were performed with enabled stability control. The data were collected during tests performed at 38.6 and 38.9 mph. Only one comparable test was performed with disabled stability control, at 40.4 mph. Recall that the test performed with disabled stability control used different handwheel inputs from those used with enabled stability control. As such, enabled and disabled stability control tests were not directly comparable. The test performed with disabled stability control is simply presented to demonstrate the effect of intervention during Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes.

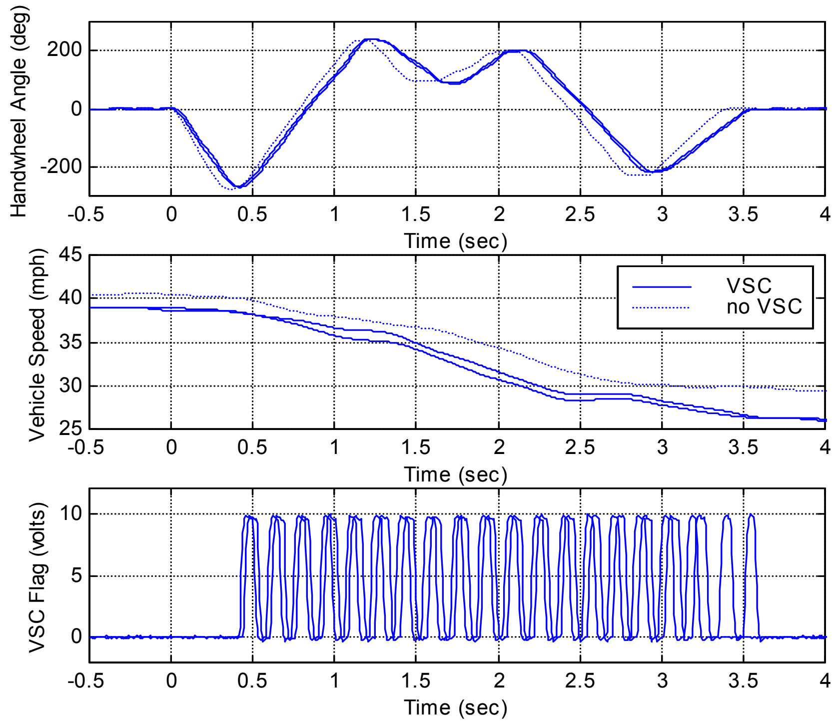


Figure 14.8. Handwheel angle, vehicle speed, and stability control intervention data for three Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes performed with the Toyota 4Runner.

When the handwheel was returned back to zero following completion of the maneuver (approximately 3.4 seconds after the maneuver was initiated), the average vehicle exit speed with stability control was 26.7 mph, 31 percent lower than the 38.8 mph average maneuver entrance speed. When stability control had been disabled, the vehicle speed was 29.9 mph, 26 percent lower than the 40.4 mph entrance speed.

Figure 14.9 presents handwheel position and vehicle speed data for four Open-Loop Pseudo CUSC Double Lane Changes performed with the Toyota 4Runner. Three of the tests shown were performed with disabled stability control. The data were collected during tests performed at 40.6, 40.5, and 40.3 mph. Only one comparable test was performed with stability control, at 39.9 mph. In a manner like that explained in the previous Open-Loop Pseudo ISO 3888 Part 2 Double Lane Change speed repeatability discussion, the test performed with enabled stability control used different handwheel input from those used with disabled stability control. As such, enabled and disabled stability control tests were not directly comparable. The test performed with enabled stability control is simply presented to demonstrate the effect of intervention during Open-Loop Pseudo CUSC Double Lane Changes.

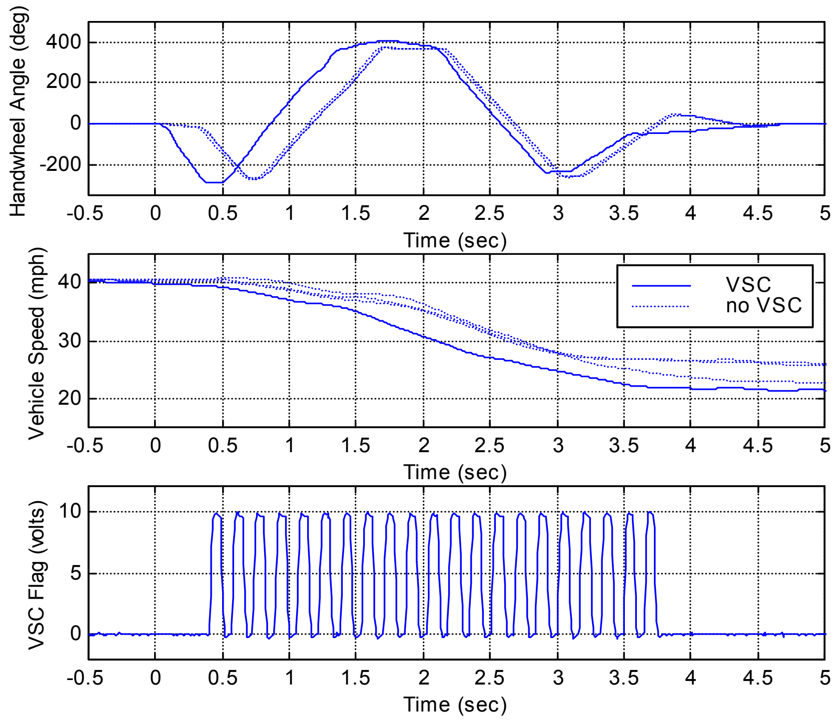


Figure 14.9. Handwheel angle, vehicle speed, and stability control intervention data for four Open-Loop Pseudo CUSC Double Lane Changes performed with the Toyota

When the handwheel was returned back to zero following completion of the maneuver (approximately 4.7 seconds after the maneuver was initiated), the vehicle speed with stability control was 21.4 mph, 46 percent lower than the 39.9 mph entrance speed. When stability control had been disabled, the average vehicle speed was 25.1 mph, 38 percent lower than the 40.5 mph average entrance speed.

14.4 Open-Loop Pseudo Double Lane Change Entrance Speed Variability

When all valid open-loop pseudo double lane change tests were considered, for each vehicle, the driver was able to achieve entrance speeds within 4.0 mph (8.0 percent) of the desired target speed. The actual and target maneuver entrance speed differed by an average of 0.9 mph (2.2 percent) overall. Open-loop pseudo double lane change entrance speed variability was in agreement with that observed during the other maneuvers performed with the steering machine.

14.5 Open-Loop Pseudo Double Lane Output Repeatability

The severity metric used for each open-loop pseudo double lane change was vehicle speed. Since, in general, multiple tests were not run at the same maneuver entrance speed, data available for the assessment of test output repeatability was limited. However, two Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes began with entrance speeds differing by only 0.3 mph.

These tests were performed with the Toyota 4Runner with enabled stability control, occurred back-to-back, and began at 38.6 and 38.9 mph. These tests allowed output repeatability assessment of the Open-Loop Pseudo ISO 3888 Part 2 Double Lane Change, although with a small sample size. Figure 14.10 presents test outputs observed during these tests. As seen in the figure, output repeatability was excellent. Also noteworthy is how repeatable the stability control intervention was found to be. Generally speaking, the application and modulation of brake line pressures during each test were very consistent, although some right front brake line pressure disparity was observed.

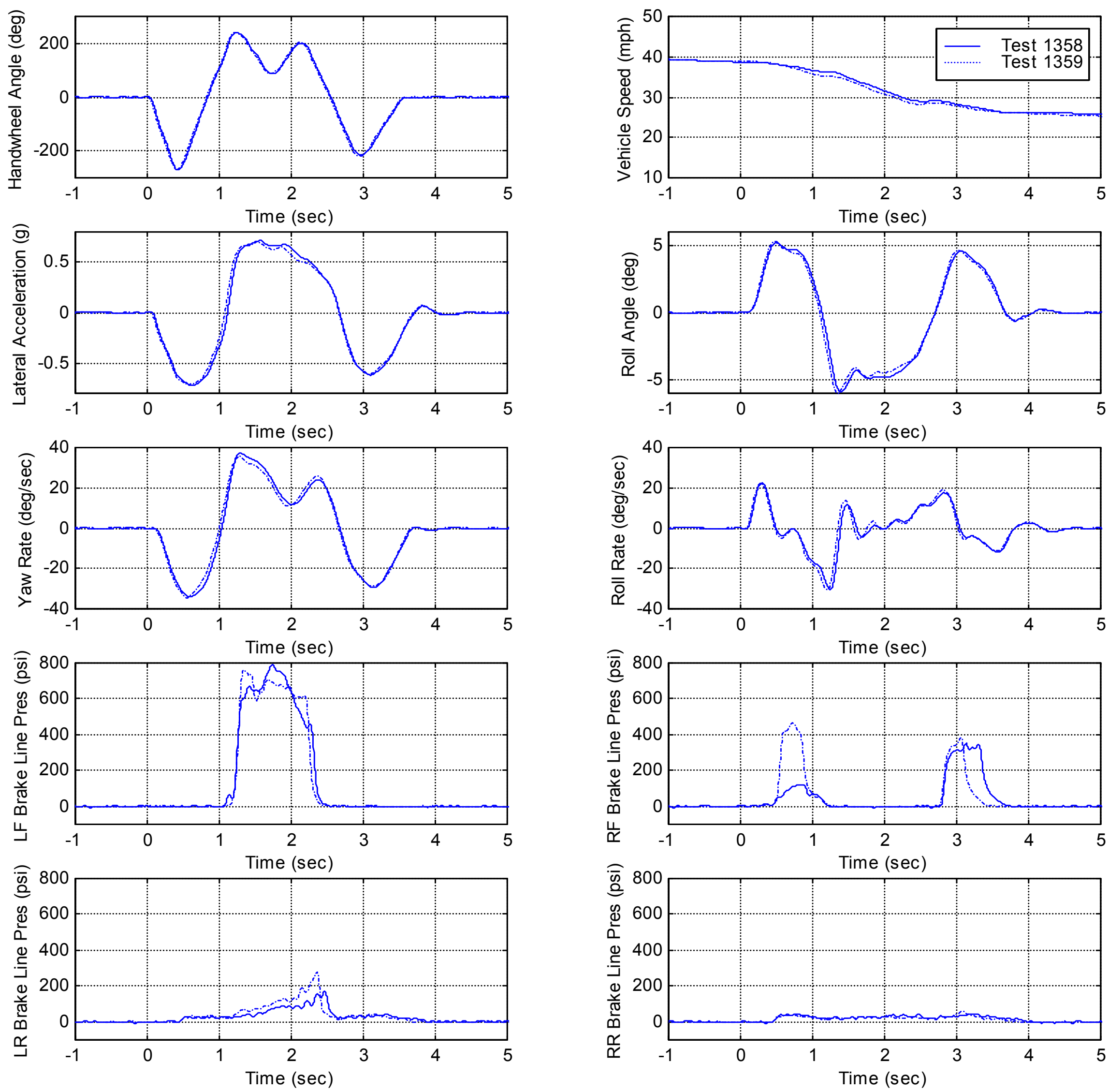


Figure 14.10 Test outputs recorded during two Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes performed with the Toyota 4Runner with enabled stability control.

Also, two Open-Loop Pseudo CUSC Double Lane Changes were performed with entrance speeds differing by only 0.4 mph. These tests were performed with the Chevrolet Blazer, occurred back-to-back, and began at 40.3 and 40.7 mph. These tests facilitated output repeatability assessment of the Open-Loop Pseudo CUSC Double Lane Change, although with a small sample size. Figure 14.11 presents test outputs observed during these tests. As seen in the figure, output repeatability was very good for first three seconds. However, some output disparity became apparent as the handwheel steering angle approached its third peak and continued for the remainder of the tests.

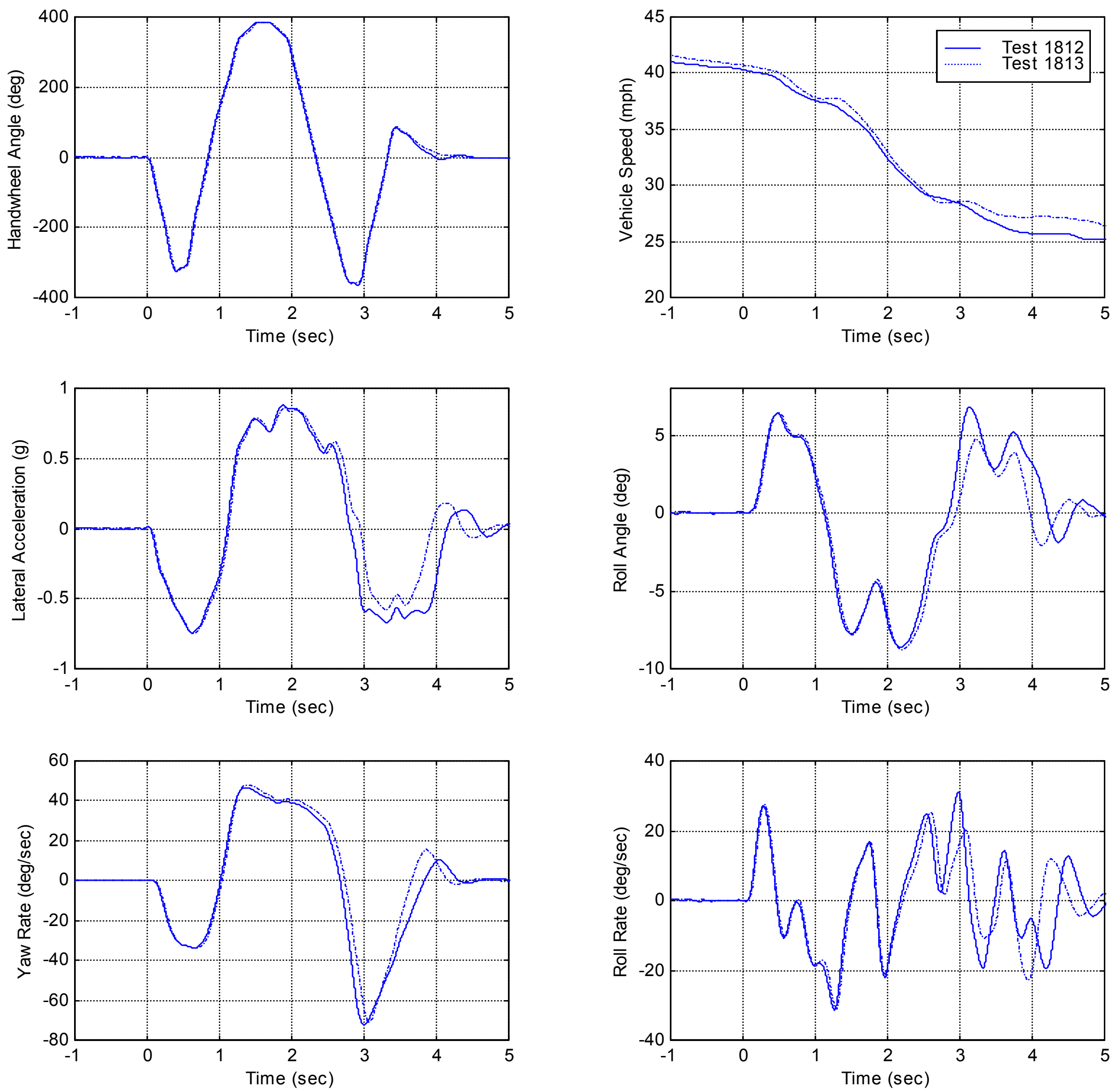


Figure 14.11 Test outputs recorded during two Open-Loop Pseudo CUSC Double Lane Changes performed with the Chevrolet Blazer.

14.6 Open-Loop Pseudo Double Lane Change Results

14.6.1 Two-Wheel Lift

Vehicle responses were in agreement with those produced during the closed-loop double lane change tests performed at similar speeds. No two-wheel lift or excessive yaw was observed when open-loop pseudo double lane changes were performed at speeds nearly equal to the maximum attained by the drivers during path-following tests. It was not until entrance speeds were increased beyond those used by the drivers during *valid* closed-loop tests that maneuver outcome was significantly affected.

Table 14.1 summarizes the two-wheel lifts produced during both open-loop pseudo double lane changes.

With one exception, each test series was performed during October 4 to 10, 2001. The authors had intended for all Phase IV open-loop pseudo double lane change testing to be performed at approximately the same time so as to minimize variation of test conditions. However, subsequent data analysis found that the simulated CUSC maneuver had been performed incorrectly when the Toyota 4Runner was evaluated with disabled stability control. To remedy the situation, this vehicle (only) was retested. The valid Open-Loop Pseudo CUSC Double Lane Change tests were performed with the 4Runner on February 8, 2002.

Table 14.1. Open-Loop Pseudo Double Lane Change Two-Wheel Lift Summary.

Vehicle	Stability Control Status	Entrance Speed Producing Two-Wheel Lift (mph)	
		Simulated ISO 3888 Part 2	Simulated CU Short Course
2001 Toyota 4Runner	Enabled	None (Max Speed = 49.5)	None (Max Speed = 49.8)
	Disabled	None[1] (Max Speed = 49.2)	42.9[2]
2001 Chevrolet Blazer	N/A	54.0	48.2

[1]Spin-outs occurred during tests performed at 43.9 and 49.2 mph.
[2]Test performed on February 8, 2002.

14.6.1.1 Pseudo ISO 3888 Part 2 Double Lane Change

The Open-Loop Pseudo ISO 3888 Part 2 Double Lane Change produced one instance of two-wheel lift with the Chevrolet Blazer. When performed at 54.0 mph (nominal speed was 50 mph), the Blazer produced two-wheel lift shortly after the second handwheel peak. No two-wheel lift occurred with the Toyota 4Runner, regardless of whether stability control was enabled or disabled. That said, excessive yaw produced during tests performed at 43.9 and 49.2 mph with disabled stability control caused the vehicle to spin-out after the second handwheel peak was input. No two-wheel lift or spinouts were produced during tests performed with enabled stability control, even with a maneuver entrance speed of 49.5 mph.

Figure 14.12 presents results from three closed-loop, path-following ISO 3888 Part 2 tests, one test per driver. Also included is one Open-Loop Pseudo ISO 3888 Part 2 Double Lane Change. All maneuvers were performed with the Toyota 4Runner, with disabled stability control, at similar entrance speeds. The closed-loop, path-following inputs of each driver in Figure 14.12 are from three of the nine tests used to define the average inputs for that driver (as described in Section 14.1).

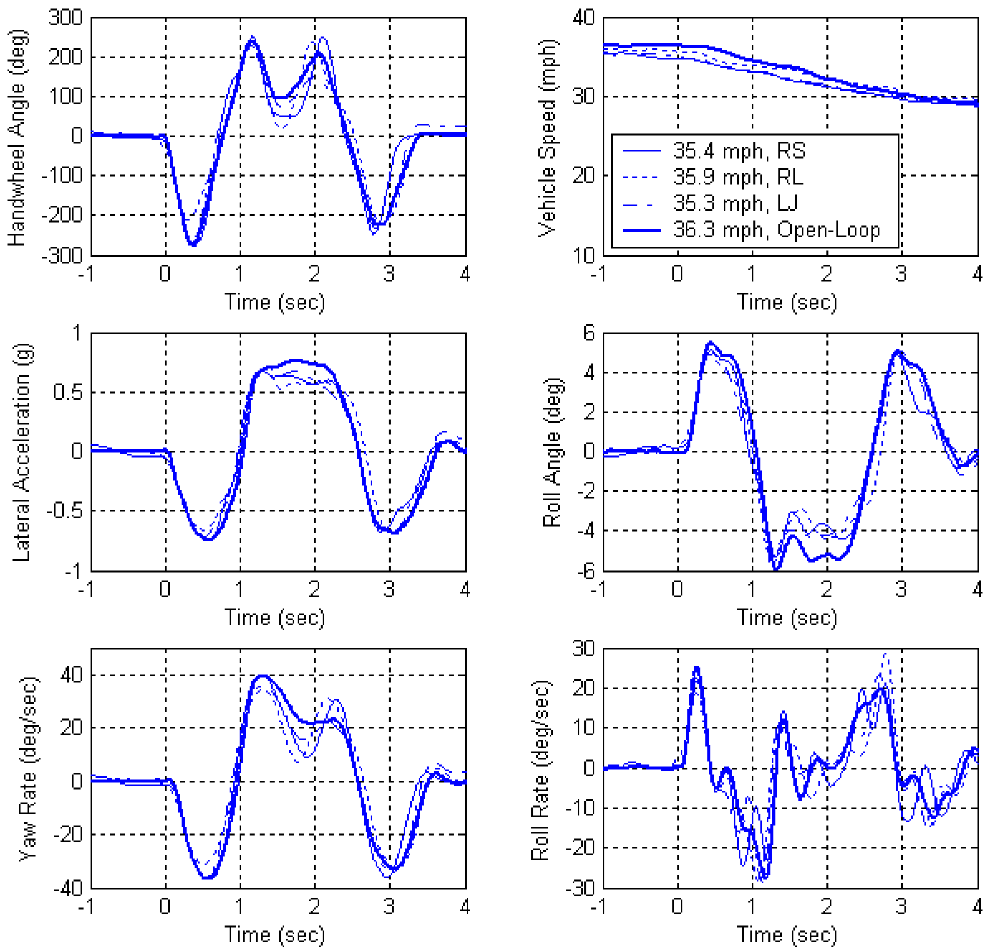


Figure 14.12. Comparison of vehicle responses produced with the Toyota 4Runner during three closed-loop, path following tests with one open-loop simulation (ISO 3888 Part 2; disabled stability control).

As Figure 14.12 shows, measured data from the open-loop simulation qualitatively matches data from the closed-loop tests. However, the open-loop simulation had a higher peak lateral acceleration and a greater roll angle during that portion of the maneuver for which the vehicle was approximately in the left lane.

Figure 14.13 compares four Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes run with the Toyota 4Runner, two tests with enabled stability control and two with it disabled. Although the tests with enabled and disabled stability control used identical handwheel inputs, their entrance speeds differed. The tests performed at 36.1 and 36.3 mph used inputs nearly the same as those recorded when the vehicle was operated at its limit by each of the three drivers during closed-loop, path-following tests (with stability control enabled and disabled, respectively). Tests performed at 49.5 mph (enabled stability control) and 49.2 mph (disabled stability control), used identical handwheel inputs but a greater maneuver entrance speed.

As Figure 14.13 shows, this substantial increase in entrance speed had only minimal effects with enabled stability control. However, with disabled stability control, a spinout occurred during the high-speed test.

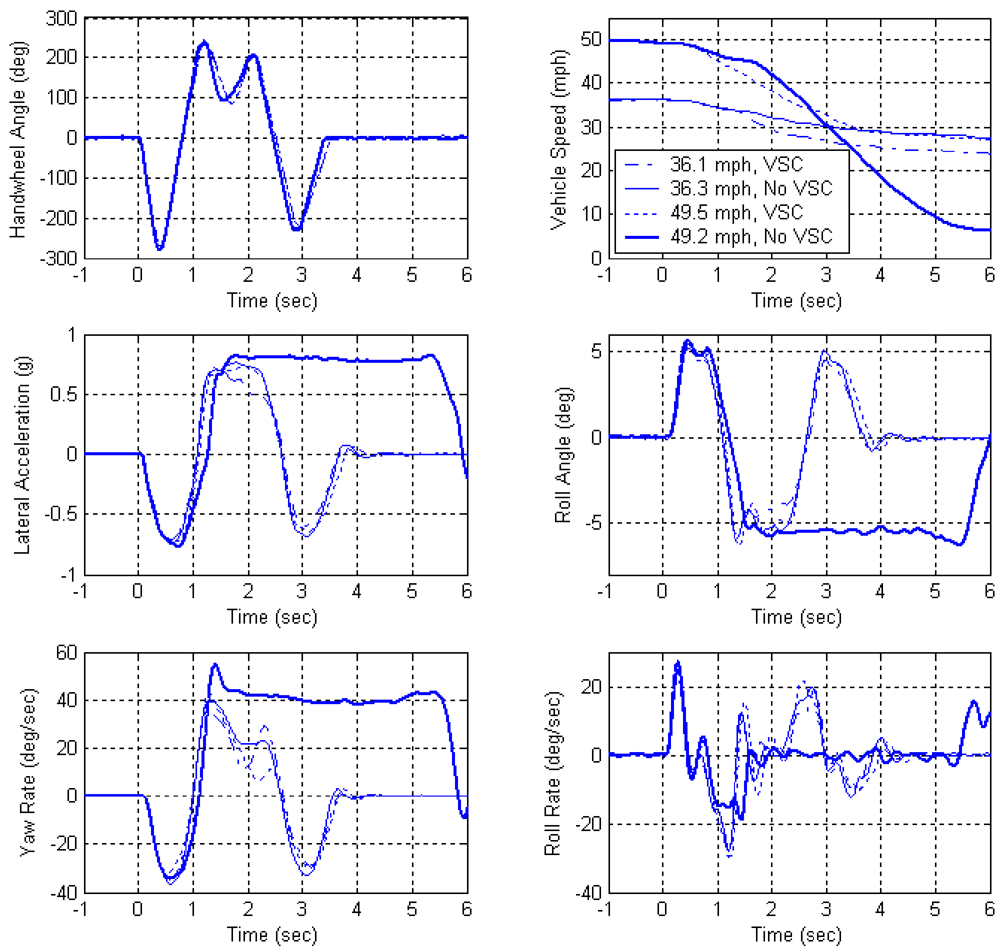


Figure 14.13. Comparison of vehicle responses produced with the Toyota 4Runner during four Open-Loop Pseudo ISO 3888 Part 2 Double Lane Changes.

14.6.1.2 Pseudo Consumers Union Short Course

The Open-Loop Pseudo CUSC Double Lane Change produced two instances of two-wheel lift, one per vehicle. When performed at 48.2 mph (nominal speed was 45 mph), the Blazer produced two-wheel lift shortly after the second handwheel peak.

No two-wheel lift was produced with the Toyota 4Runner when stability control was enabled, even with a maneuver entrance speed of 49.8 mph. When stability control was disabled, two-wheel lift occurred during a test performed with an entrance speed of 42.9 mph. Like the Blazer, the 4Runner produced two-wheel lift shortly after the second handwheel peak.

Figure 14.14 presents results from three closed-loop, path-following CUSC tests, one test per driver. Also included is one Open-Loop Pseudo CUSC Double Lane Change. All maneuvers were performed with the Chevrolet Blazer at similar entrance speeds. The closed-loop, path-following inputs of each driver in Figure 14.14 are from three of the nine tests used to define the average inputs for that driver (as described in Section 14.1).

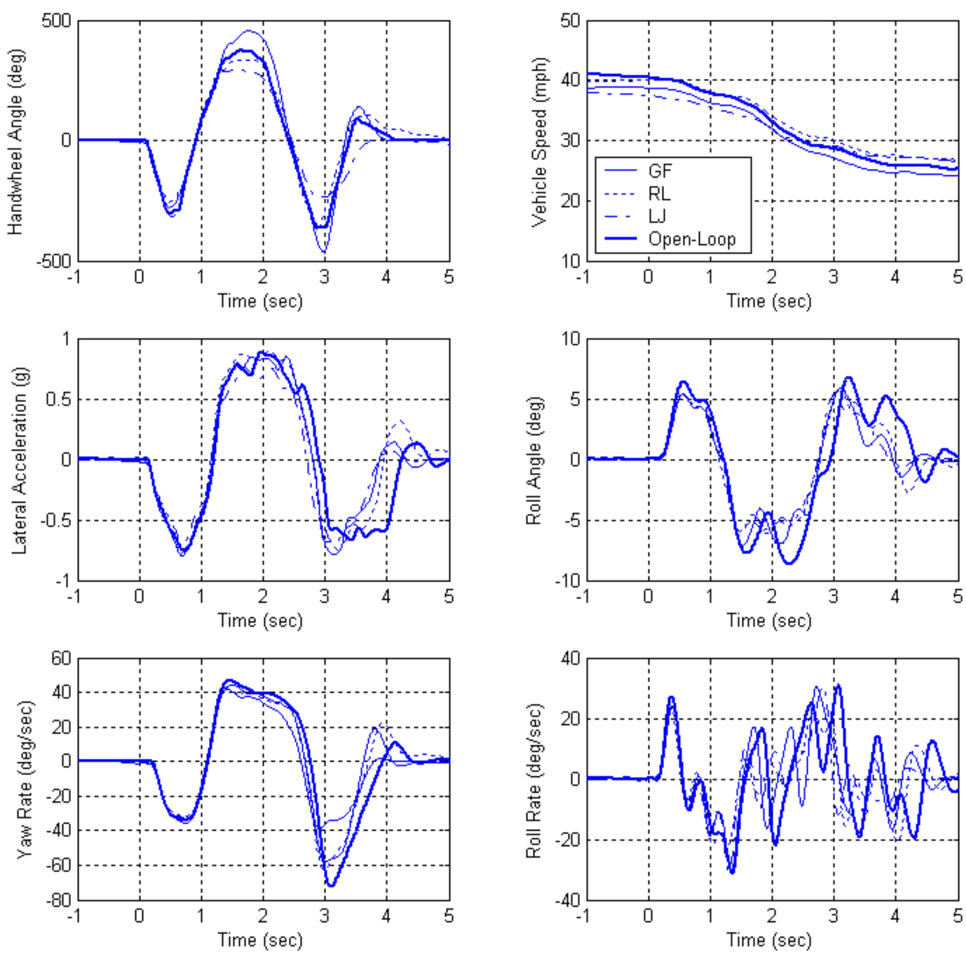


Figure 14.14. Comparison of vehicle responses produced with the Chevrolet Blazer during three closed-loop, path following tests with one open-loop simulation (CUSC).

As Figure 14.14 shows, measured data from the open-loop simulation qualitatively matches data from the closed-loop tests. However, the open-loop simulation had a higher peak yaw rate and roll angle.

Figure 14.15 compares two Open-Loop Pseudo CUSC Double Lane Changes performed with the Chevrolet Blazer. Although the tests used identical handwheel inputs, their entrance speeds differed. The test performed at 40.2 mph used inputs nearly the same as those used when the vehicle was operated at its limit by each of the three drivers during closed-loop, path-following tests and did not produce two-wheel lift or excessive yaw. The test performed at 48.2 mph used identical handwheel inputs but a greater maneuver entrance speed.

As Figure 14.15 shows, this substantial increase in entrance speed strongly affected the vehicle response. Two-wheel lift occurred during the high-speed (48.2 mph) test.

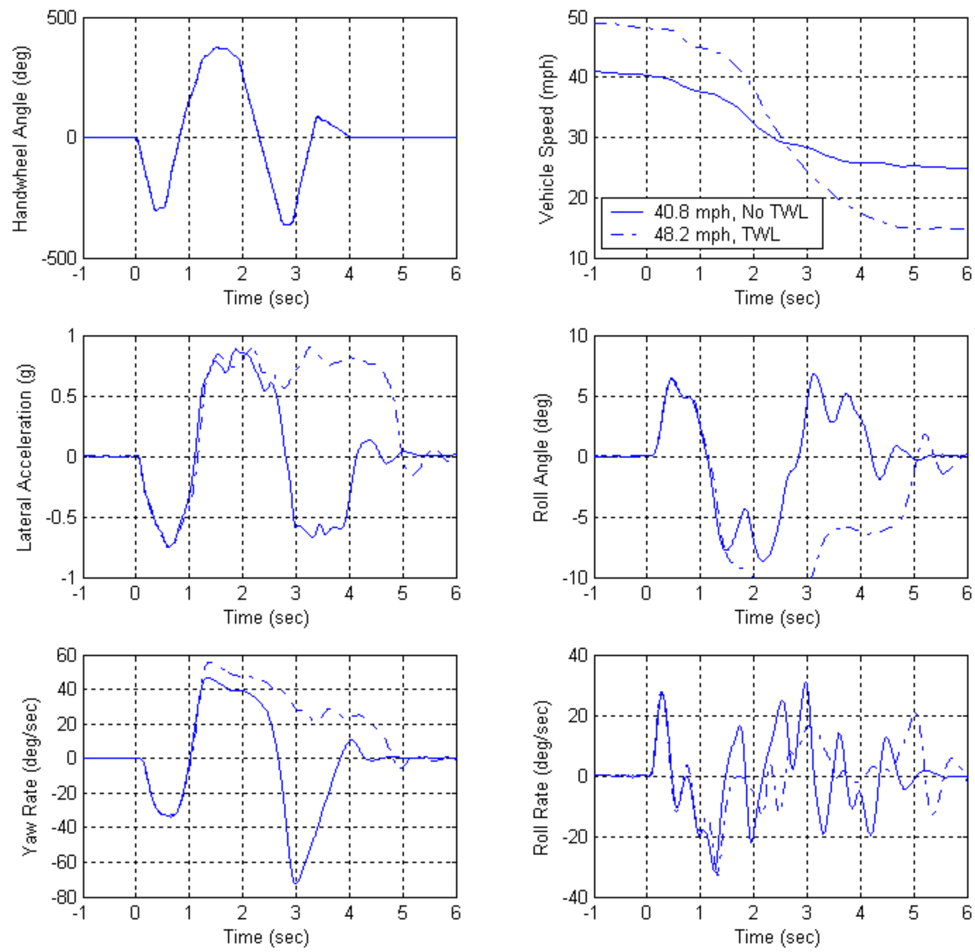


Figure 14.15. Comparison of vehicle responses produced with the Chevrolet Blazer during two Open-Loop Pseudo CUSC Double Lane Changes.

14.6.2 Tire Debeading and Rim Contact

No tire debeads or instances of rim-to-pavement contact were observed during either open-loop pseudo double lane change test series.

14.7 Open-Loop Pseudo Double Lane Change Maneuver Assessment

Using the criteria presented in Chapter 2, the authors have rated the Open-Loop Pseudo Double Lane Change maneuvers in the following manner (the ratings of the Consumers Union Short Course and ISO 3888 Part 2 simulations are the same):

Objectivity and Repeatability = Satisfactory

Open-Loop Pseudo Double Lane Changes were performed with excellent objectivity and input repeatability. By using the programmable steering machine, handwheel inputs were precisely executed, and able to be replicated from run-to-run. Test drivers were able to achieve maneuver entrance speeds an average of ± 0.9 mph from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data produced by the first two handwheel inputs (Initial Steer and Reversal #1) were highly repeatable. However, responses to the third steering input (Reversal #2) could be quite disparate. This disparity was most apparent when the maneuvers were begun at high entrance speeds. For this reason, the Objectivity and Repeatability rating for the Open-Loop Pseudo Double Lane Change was reduced from excellent to satisfactory.

Although the Open-Loop Pseudo Double Lane Changes provided very limited two-wheel lift data for consideration, it should be noted that the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) can be, at times, lower than that observed at other speeds. Even when nearly identical steering and speed inputs are achieved, small response fluctuations (due to test-to-test variability) may be apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Since this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of the Open-Loop Pseudo Double Lane Change maneuvers.

Performability = Satisfactory

Objective and repeatable Open-Loop Pseudo Double Lane Change maneuvers were easily performed using the programmable steering controller. The test procedure was straightforward, and because the handwheel inputs were based on those used by actual drivers during closed-loop, path-following tests, they were directly related to the vehicle being evaluated. These approximations were not expected, nor intended, to emulate steering of tests performed at different entrance speeds. Open-loop pseudo double lane changes were performed to investigate how a third major handwheel peak (i.e., two steering reversals) may affect dynamic rollover propensity.

While running this maneuver is straightforward, the authors have substantial concerns about the maneuver itself. Unfortunately, due to lack of development time, it is doubtful the steering inputs used during the Phase IV Rollover Research correspond to worst-case conditions (test drivers were unable to produce two-wheel lift during any valid closed-loop double lane change). Determination of how to adapt this maneuver to different vehicles sizes or characteristics is still needed. It is estimated at least one year of effort would be required to develop and refine this maneuver.

Furthermore, Open-Loop Pseudo Double Lane Changes required considerable testing time and cost to provide the data necessary to derive the handwheel inputs of each test vehicle.

For the above listed reasons, the authors can rate the Performability of this maneuver as no better than satisfactory.

Discriminatory Capability = Very Bad

Open-Loop Pseudo Double Lane Change tests were performed with two vehicles, the Chevrolet Blazer and Toyota 4Runner (with enabled and disabled stability control). For each vehicle, two suites of maneuvers were used: those that simulated handwheel inputs used during ISO 3888 Part 2 tests, and those simulated handwheel inputs used during Consumers Union Short Course tests. All Open-Loop Pseudo Double Lane Change tests were performed in the Nominal Load configuration.

Two-wheel lift was produced during simulated ISO 3888 Part 2 testing performed with the Chevrolet Blazer. No two-wheel lift was produced with the Toyota 4Runner, regardless of whether stability control was enabled or disabled. However, the maneuver entry speed at which the Chevrolet Blazer had two-wheel lift was 4.8 mph higher than the maximum speed at which Toyota 4Runner testing was stopped. When yaw stability control was disabled, the speed at which Toyota 4Runner testing was stopped was determined by when spinout occurred. When yaw stability control was enabled, the speed at which Toyota 4Runner testing was stopped was determined by test driver concerns about possible loss of control. Therefore it is possible that two-wheel lift was seen for the Chevrolet Blazer but not the Toyota 4Runner because the Blazer was able to perform this maneuver at higher speeds than was the 4Runner. As was the case for the actual ISO 3888 Part 2 Double Lane Change, handling and rollover resistance appear to be inextricably intertwined in the ratings produced by this maneuver.

Two-wheel lift was produced during simulated Consumers Union Short Course testing performed with the Chevrolet Blazer *and* the Toyota 4Runner with disabled stability control. The maneuver entry speed at which the Chevrolet Blazer had two-wheel lift was higher than the maximum speed at which Toyota 4Runner two-wheel lift occurred. However, based on its one star rating and performance in the NHTSA J-Turn and Fishhooks, the authors believe the Chevrolet Blazer to have the lowest rollover resistance of any of the Phase IV rollover test vehicles. The explanation for this apparent anomaly is that, as was the case for the actual Consumers Union Short Course Double Lane Change, handling and rollover resistance appear to be inextricably intertwined in the ratings produced by this maneuver.

Because this maneuver is not focused solely on a vehicle's rollover resistance but instead measures some combination of handling and rollover resistance properties, its Discriminatory Capability for rollover resistance is rated as very bad.

Appearance of Reality = Excellent

In general, double lane change maneuvers have excellent appearance of reality. The handwheel inputs defining the Open-Loop Pseudo Double Lane Changes approximate the steering a driver might use in an emergency obstacle avoidance maneuver performed on a two-lane road.

15.0 MANEUVER COMPARISONS

15.1 Two-Wheel Lift

Figures 15.1 through 15.6 summarize the two-wheel lifts (or absence thereof) that occurred during the NHTSA J-Turn, NHTSA Fishhooks 1a and 1b, Nissan Fishhook, and Open-Loop Pseudo Double Lane Change maneuvers. Figures 15.1 and 15.2 show Nominal Load two-wheel lifts. Figures 15.3 and 15.4 show lifts for the Reduced Rollover Resistance configuration. Finally, Figures 15.5 and 15.6 show Modified Handling lifts.

Note that the final test performed in some J-Turn test series was performed below the nominal termination speed of 60 mph, as indicated by the vertical bars extending down from 60 mph without a speed below them in Figures 15.1 through 15.4. This was not intentional, but rather the byproduct of the maneuver entrance speed variability discussed in previous chapters. It is important that these bars *not* be interpreted as indicators of two-wheel lift. If two-wheel lift occurred during a particular test series, the speed at which it occurred is shown below the bar.

Similarly, the final test performed in some Fishhook test series was performed below the nominal termination speed of 50 mph, as indicated by the vertical bars extending down from 50 mph without a speed below them in Figures 15.1 through 15.4. Again, these bars do *not* indicate that two-wheel lift. If two-wheel lift occurred during a particular test series, the speed at which it occurred is shown below the bar.

15.1.1 NHTSA J-Turn and Fishhooks

All three fishhook maneuvers produced two-wheel lift for vehicles in the Nominal Load configuration, while the NHTSA J-Turn and the closed-loop, path-following double lane changes did not. Two-wheel lift occurred during fishhook tests performed with the Chevrolet Blazer and Mercedes ML320 in their Nominal Load configuration. Fishhooks 1a and 1b both produced two-wheel lift during ML320 tests performed both with enabled and disabled stability control. The maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

For vehicles in the Reduced Rollover Resistance configuration, the NHTSA J-Turn and Fishhooks produced two-wheel lift. Compared to Nominal Load results, the Chevrolet Blazer required lower maneuver entrance speeds to produce two-wheel lift in the Reduced Rollover Resistance configuration[1]. Unlike the Nominal Load configuration tests, NHTSA J-Turns performed with vehicles in the Reduced Rollover Resistance configuration produced two-wheel lift for every vehicle except the Ford Escape.

[1] Recall that Fishhook 1a and 1b tests were not performed with the Mercedes ML320 in the Reduced Rollover Resistance configuration due to test driver safety concerns. Since two-wheel lift occurred during Nominal Load configuration ML320 tests, the authors believe it would have certainly occurred in the Reduced Rollover Resistance configuration. The roof-mounted ballast used in this configuration reduced rollover resistance, thereby increasing rollover propensity compared to the Nominal Load.

The NHTSA J-Turn maneuver produced two-wheel lift during Mercedes ML320 tests performed both with enabled and disabled stability control. The maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control. Similarly, the Fishhooks 1a and 1b both produced two-wheel lift during Toyota 4Runner tests performed both with enabled and disabled stability control. Again, the maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

The Modified Handling configuration imposed different demands on the vehicles depending upon how this test configuration was achieved. Installation of optional wheel/tire packages did not increase the rollover propensity of the Ford Escape or Mercedes ML320. Although two-wheel lift occurred during tests performed with the ML320, each of these tests began with maneuver entrance speeds greater than the 50 mph maximum nominal value. The Fishhook 1b maneuver produced two-wheel lift during ML320 tests performed both with enabled and disabled stability control. Again, the maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

Simultaneously loading the Toyota 4Runner to GVWR and rear GAWR did not adversely affect its rollover propensity. This loading had a very pronounced effect on the Chevrolet Blazer's rollover resistance. When left-right steering was input in this configuration, two-wheel lift occurred at a maneuver entrance speed of 34.9 mph.

Based on their ability to produce two-wheel lift, the fishhook maneuvers were the most effective Dynamic Rollover Propensity tests used in Phase IV, regardless of the loading configuration. The NHTSA Fishhook 1a and 1b maneuvers were the most effective of the fishhooks, and their results were generally in good agreement.

15.1.2 Nissan Fishhook

Only the Chevrolet Blazer and Ford Escape were tested using the Nissan Fishhook maneuver. While two-wheel lift was produced with the Nissan Fishhook during tests performed with the Blazer, its occurrence was associated with a higher maneuver entrance speed than required for Fishhook 1a or 1b. Furthermore, the Nissan Fishhook produced two-wheel lift only when left-right steering was input.

15.1.3 Closed-Loop, Path-Following Double Lane Changes

No two-wheel lift occurred during any valid ("clean") closed-loop, path-following double lane change, even when the vehicles were evaluated in the Reduced Rollover Resistance configuration (using the ISO 3888 Part 2 course). For this reason, Ford PCL LC, ISO 3888 Part 2, and Consumers Union Short Course results were not included in Figures 15.1 through 15.6.

15.1.4 Open-Loop Pseudo Double Lane Changes

Open-Loop Pseudo Double Lane changes were performed with the Chevrolet Blazer and Toyota 4Runner only. The 4Runner tests were performed with stability control enabled and disabled. When performed with maneuver entrance speeds approximately equal to the maximum “clean” run speeds successfully attained by each of the three test drivers during closed-loop, path-following double lane change testing, two-wheel lift did not occur for either vehicle, regardless of stability control status. However, when maneuver entrance speeds were increased above those achieved by test drivers, two-wheel lift *did* occur. In the case of the Blazer, two-wheel lift occurred during both simulated Consumers Union Short Course and ISO 3888 Part 2 tests. The maneuver entrance speeds at which two-wheel lift occurred for these tests were greater than those that produced two-wheel lift during the fishhook maneuvers. For the 4Runner, no two-wheel lifts occurred during tests with stability control enabled. When stability control was disabled, no two-wheel lifts occurred during simulated ISO 3888 Part 2 tests, however, it happened during a simulated Consumers Union Short Course test.

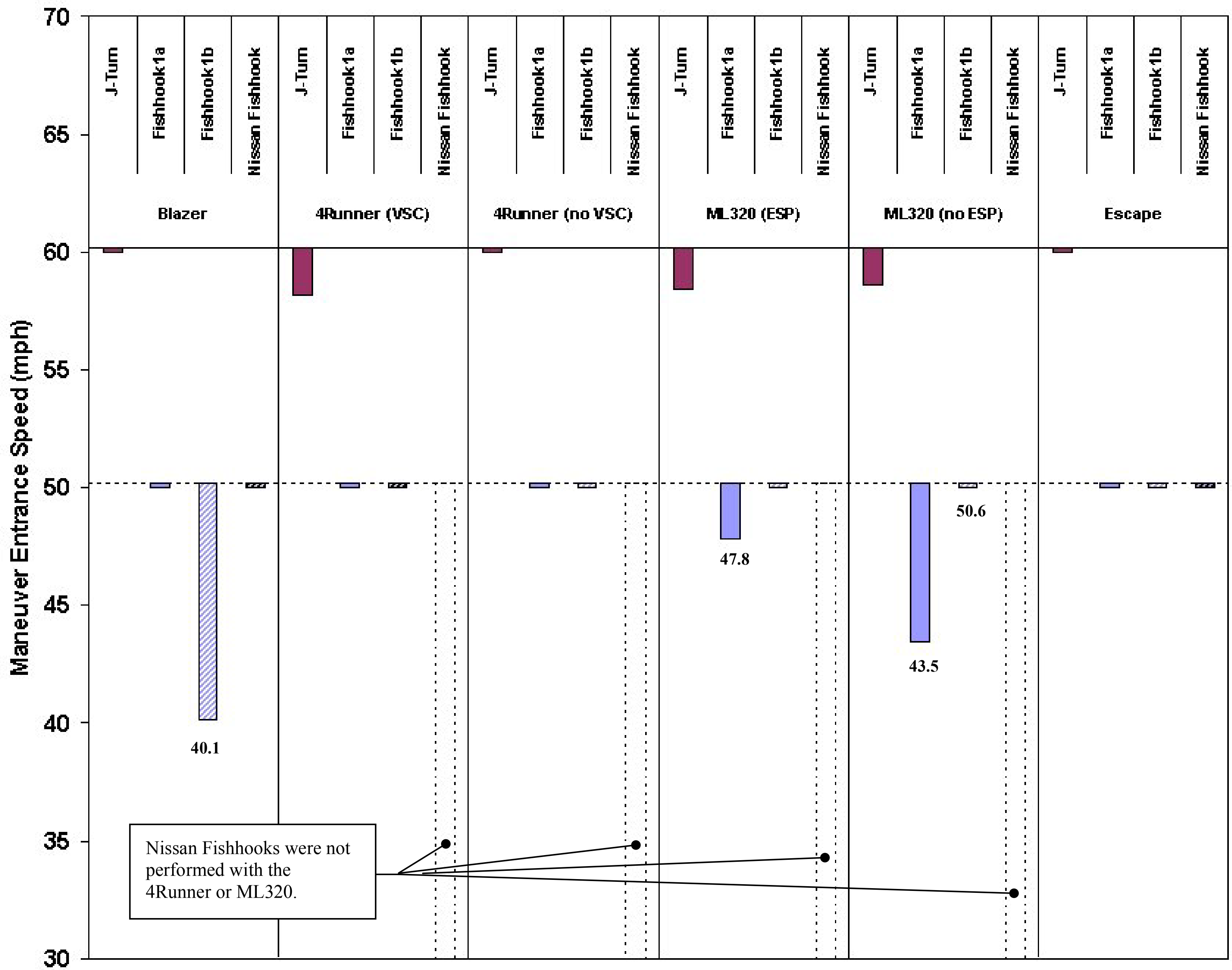


Figure 15.1. Overall two-wheel lift summary for left-steer J-Turns and right-left Fishhooks performed in the Nominal Load configuration. Entrance speeds of the tests producing two-wheel lift are provided. If no speed is given, two-wheel lift was not observed.

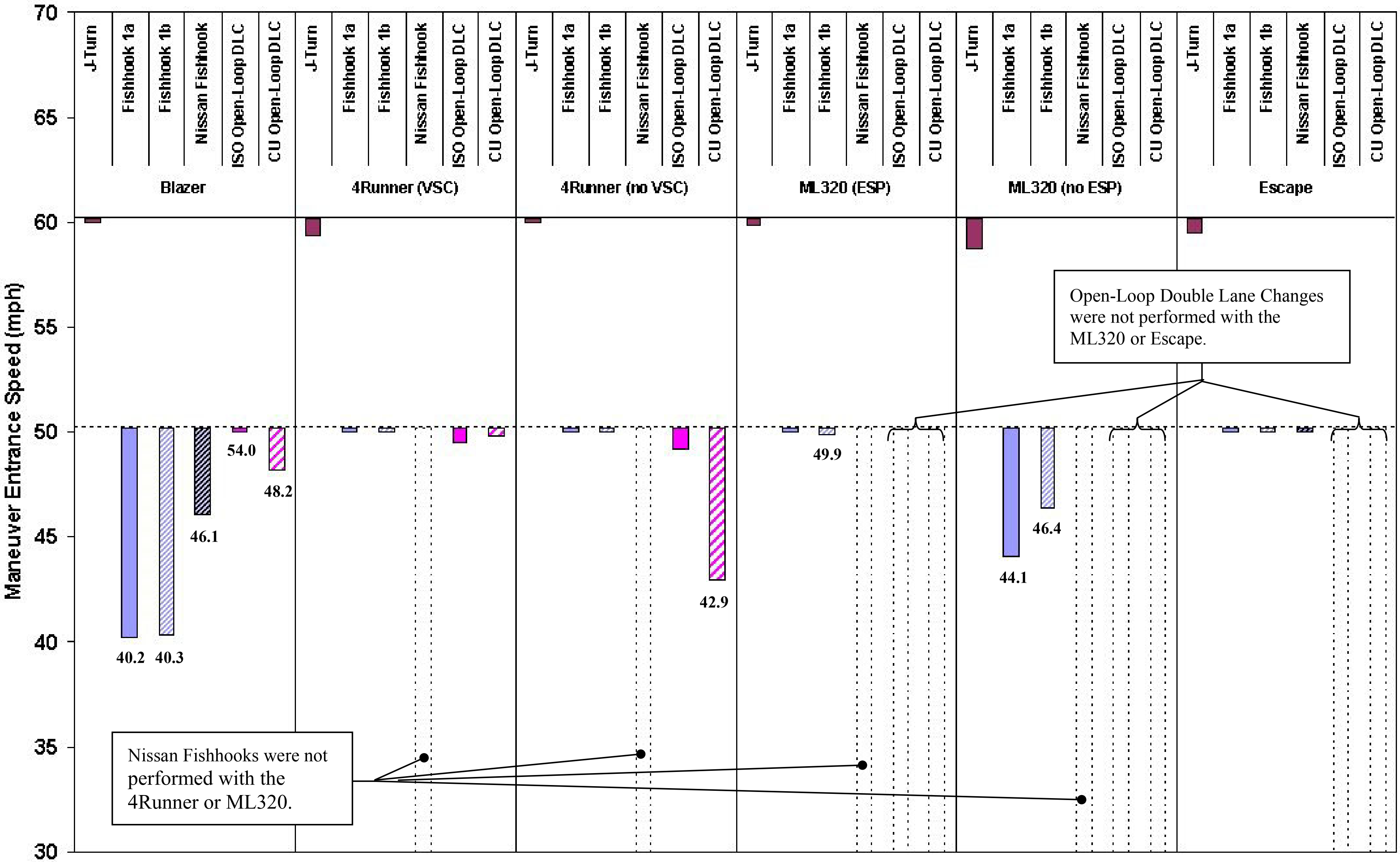


Figure 15.2. Overall two-wheel lift summary for right-steer J-Turns, left-right Fishhooks, and left-right-left Open-Loop Pseudo Double Lane Changes performed in the Nominal Load configuration. Entrance speeds of the tests producing two-wheel lift are provided. If no speed is given, two-wheel lift was not observed.

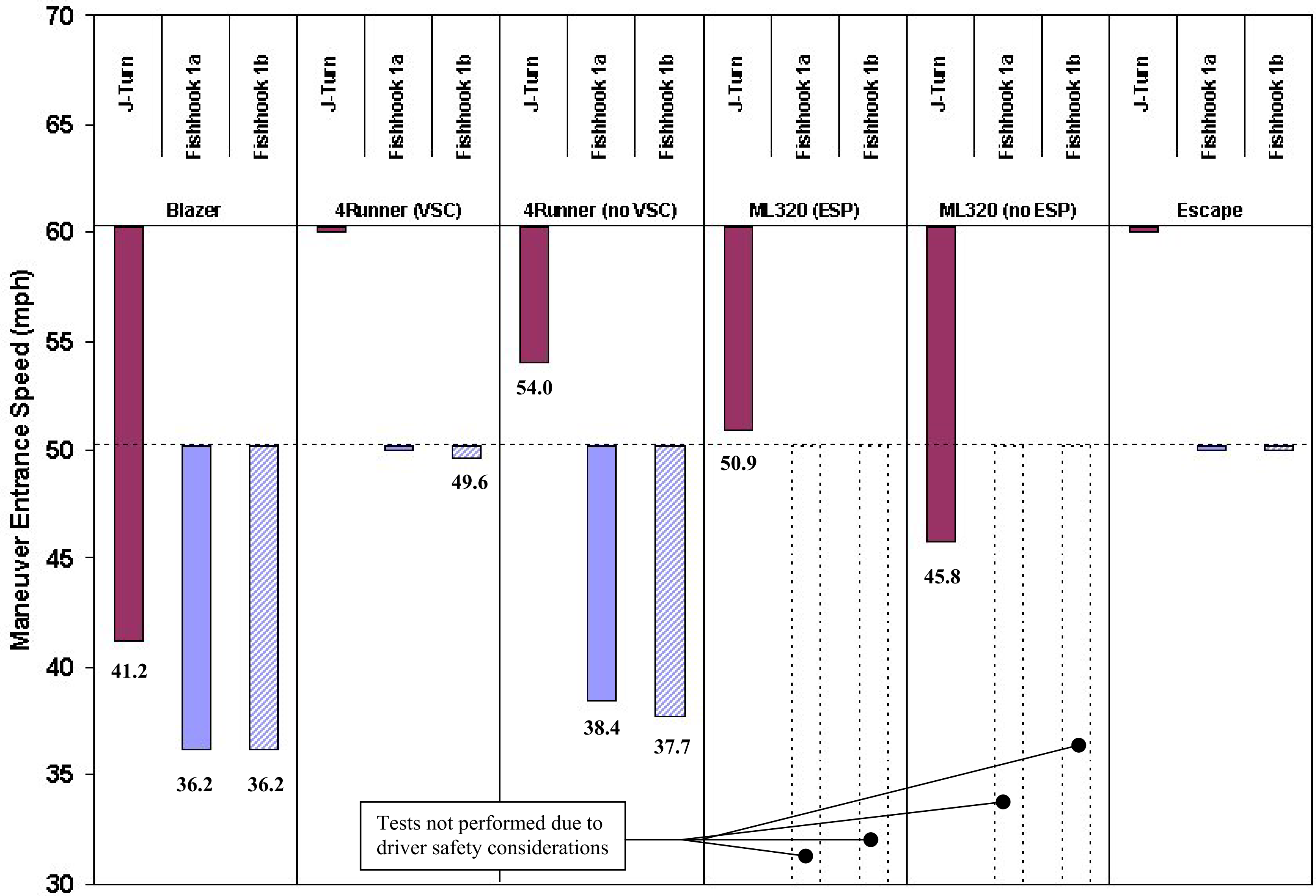


Figure 15.3. Overall two-wheel lift summary for left-steer J-Turns and right-left Fishhooks performed in the Reduced Rollover Resistance configuration. Entrance speeds of the tests producing two-wheel are provided. If no speed is given, two-wheel lift was not observed.

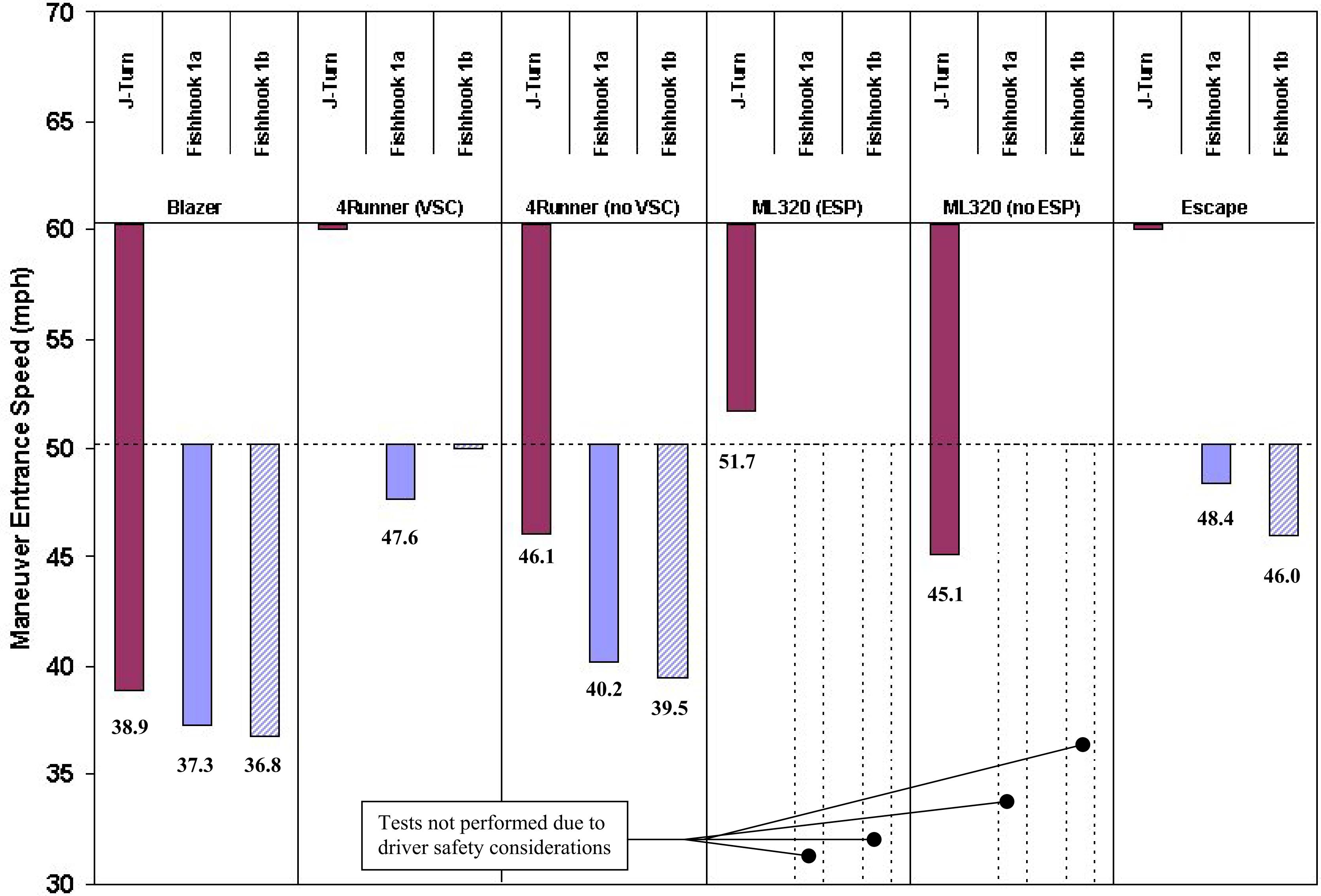


Figure 15.4. Overall two-wheel lift summary for right-steer J-Turns and left-right Fishhooks performed in the Reduced Rollover Resistance configuration. Entrance speeds of the tests producing two-wheel lift are provided. If no speed is given, two-wheel lift was not observed.

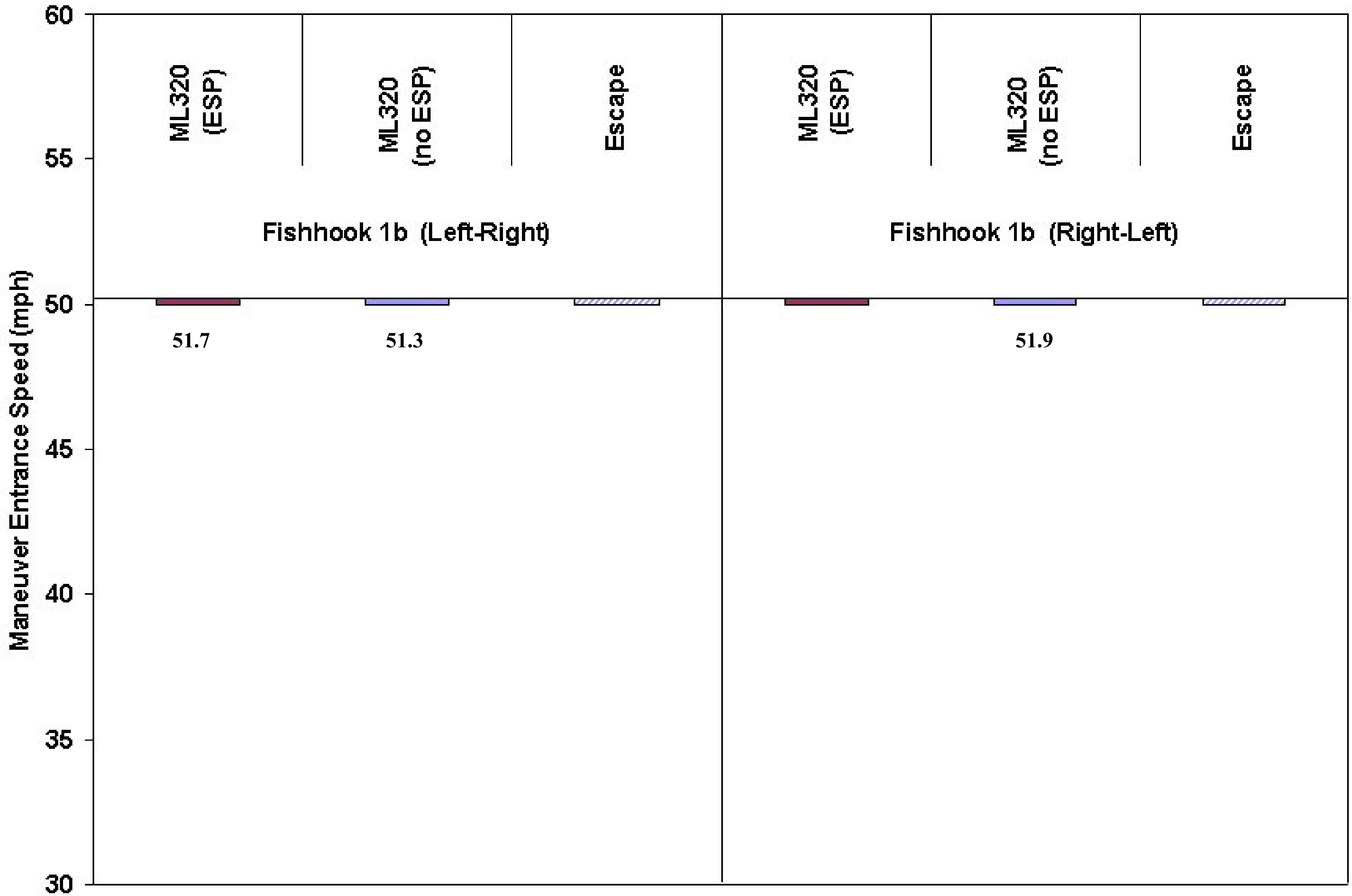


Figure 15.5. Overall two-wheel lift summary for Fishhook 1b tests performed in the Modified Handling configuration with alternative wheels/tire packages. Entrance speeds of the tests producing two-wheel lift are provided. If no speed is given, two-wheel lift was not observed.

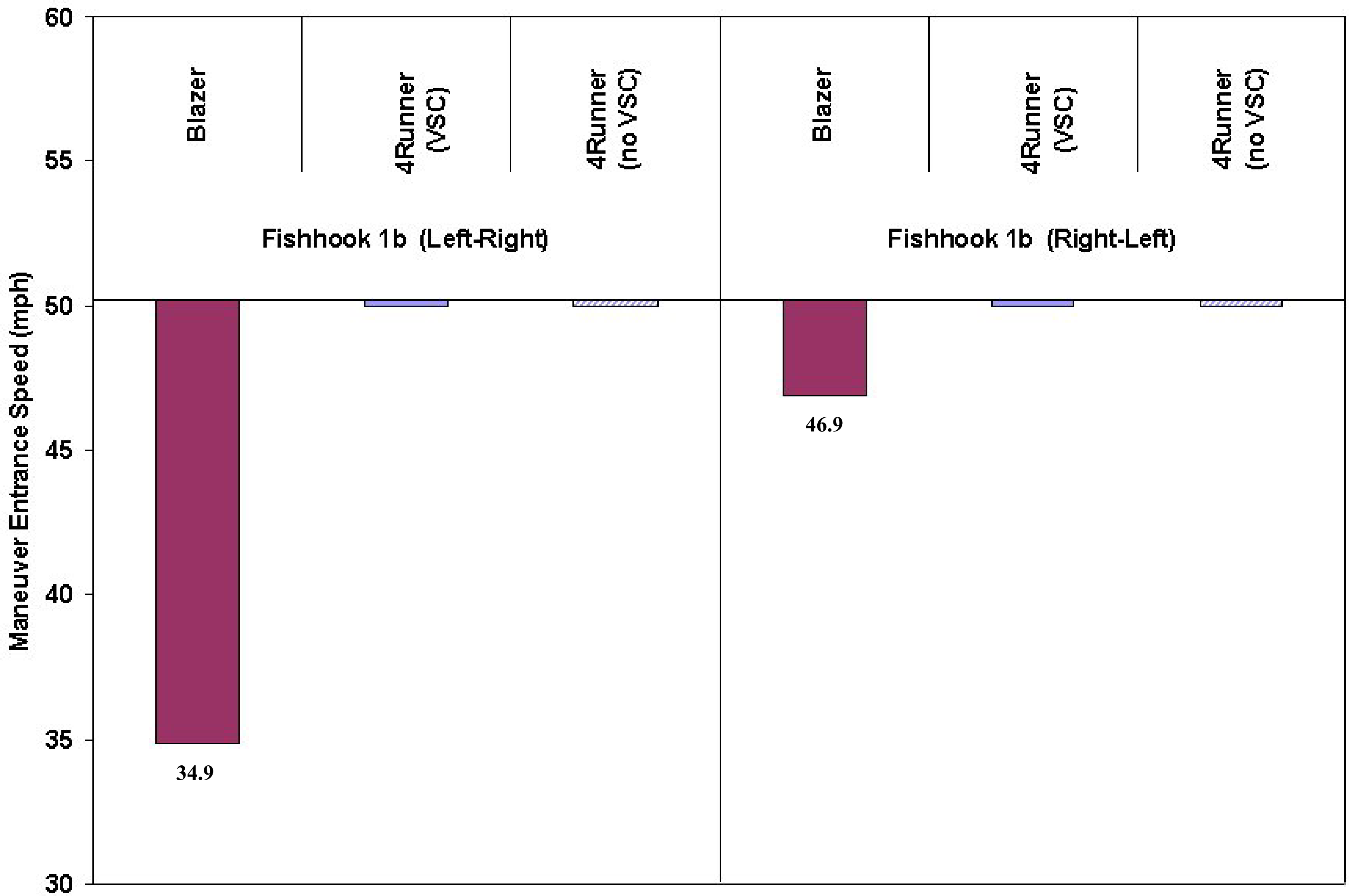


Figure 15.6. Overall two-wheel lift summary for Fishhook 1b tests performed in the Modified Handling configuration with rear-mounted ballast. Entrance speeds of the tests producing two-wheel lift are provided. If no speed is given, two-wheel lift was not observed.

15.2 Fishhook Dwell Times

In a fishhook maneuver, the handwheel angle dwell time can have a substantial effect as to how successful a particular combination of steering inputs is in producing two-wheel lift. Both the Fishhook 1b and Nissan Fishhook maneuvers endeavored to be “worst-case” maneuvers by maximizing the roll momentum of each test vehicle during the countersteer. For both maneuvers, this was accomplished by optimizing dwell time.

The manner in which Fishhook 1b and Nissan Fishhook dwell times were determined differed greatly. The Fishhook 1b relied on the use of roll rate feedback to determine the timing of the handwheel reversals. Therefore, the timing of each Fishhook 1b maneuver was optimized for the test conditions on a “run-to-run” basis (i.e., vehicle configuration, maneuver entrance speed, surface coefficient of friction, etc.). The Nissan Fishhook used an iterative methodology to determine timing. While this methodology optimized maneuver timing for the test conditions, it involved a time-consuming process used to define dwell times for a block of tests (tests begun within a particular range of maneuver entrance speeds). Instead of run-by run optimization, the Nissan Fishhook procedure performs dwell time optimization for blocks of tests.

Despite the use of very different approaches, the dwell times associated with the lowest maneuver entrance speeds capable of producing two-wheel lift with the Chevrolet Blazer were identical for Fishhook 1b and Nissan Fishhook tests preformed with left-right steering, as shown in Table 15.1.

Table 15.1. Handwheel Dwell Times of the Tests Producing Two-Wheel Lift with the Lowest Entrance Speeds.

Vehicle	Fishhook 1b		Nissan Fishhook	
	Left-Right	Right-Left	Left-Right	Right-Left
Chevrolet Blazer	40 ms	30 ms	40 ms	--

Note: All tests presented in Table 15.1 were performed in the Nominal Load configuration.

While these results are interesting, it is important to recall the Fishhook 1b and Nissan Fishhook entrance speeds of the tests producing two-wheel lift were not equal, and that two-wheel lift was not produced when Nissan Fishhook tests were performed with right-left steering (whereas right-left Fishhook 1b tests did produce two-wheel lift). Also, Table 15.1 only includes three dwell times. For this reason, consideration of dwell times during all comparable test series (tests performed in the Nominal Load configuration) provides a much better comparison of how similar the output of the two maneuvers actually were.

Figure 15.7 is a graphical comparison of dwell times during Fishhook 1b and Nissan Fishhook tests performed with the Chevrolet Blazer and Ford Escape. Data from tests performed with left-right and right-left steering are provided. For reference purposes, Fishhook 1a dwell time data are also provided. Despite the use of different handwheel magnitudes and rates, the Fishhook 1b and Nissan Fishhook dwell times of each series, for each vehicle, were in good agreement.

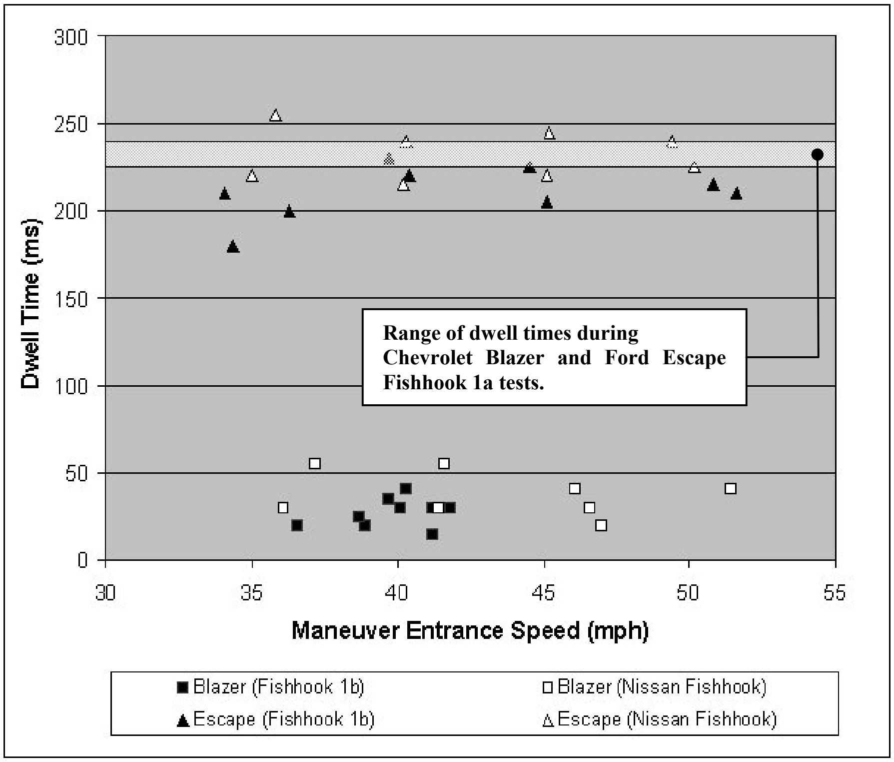


Figure 15.7. Fishhook dwell time comparison for tests performed with the Chevrolet Blazer and Ford Escape.

15.2.1 Chevrolet Blazer

For the Chevrolet Blazer, actual Fishhook 1b dwell times ranged from 15 to 40 ms during a test series of 10 tests begun with maneuver entrance speeds ranging from 36.1 to 41.8 mph. The Nissan methodology indicated that a commanded dwell time of 100 ms would be optimal for the speed range of 35 to 40 mph[2]. When this dwell time was commanded, the steering machine produced actual dwell times ranging from 20 to 55 ms during a test series of eight tests. The dwell times of all but one Fishhook 1b test were contained within the range of actual Nissan Fishhook dwell times.

Although dwell times used during each test series were similar, Fishhook 1b produced two-wheel lift at a lower maneuver entrance speed when left-right steering was used. Furthermore, the Nissan Fishhook was unable to produce two-wheel lift when right-left steering was used, whereas the Fishhook 1b produced two-wheel lift at 40.1 mph. This implies that while correct dwell time specification is important, it must be used in conjunction with correct handwheel magnitudes and rates for fishhook maneuver effectiveness to be optimized. Based on

[2] The commanded dwell time and actual dwell times differed due to the responsiveness of the steering machine. For this reason, comparing the commanded Nissan Fishhook dwell time to the range of dwell times observed in Fishhook 1b is *not* appropriate. Such comparison must use actual Nissan Fishhook dwell times to be meaningful.

comparison of Fishhook 1b and Nissan Fishhook results from tests performed with the Blazer, the authors do not believe that Nissan Fishhook steering inputs are optimal.

15.2.2 Ford Escape

For the Ford Escape, Fishhook 1b dwell times ranged from 180 to 230 ms during a test series of nine tests performed from 34.1 to 51.6 mph. The Nissan methodology indicated that a commanded dwell time of 300 ms would be optimal for the speed range of 35 to 50 mph. When this dwell time was commanded, the steering machine produced actual dwell times ranging from 215 to 255 ms during a test series of eight tests. Unlike the results of the Chevrolet Blazer dwell time comparison previously discussed, most Ford Escape Fishhook 1b dwell times were lower than those of the actual Nissan Fishhook values; four of the nine Fishhook 1b dwell times were contained within the range of actual dwell times commanded with a constant dwell time. There was considerable overlap of the two dwell time ranges of test series.

No two-wheel lifts occurred during Fishhook 1b or Nissan Fishhook tests performed with the Ford Escape in the Nominal Load configuration. Although two-wheel lift occurred with the Escape during Fishhook 1b tests performed in the Reduced Rollover Resistance configuration, Nissan Fishhooks were not performed with vehicles in this configuration. Therefore, a comparison of Fishhook 1b and Nissan Fishhook maneuver effectiveness (based on the ability of the maneuver to produce two-wheel lift) was not possible for Escape.

15.3 Handwheel Inputs: J-Turns and Fishhooks vs. Closed-Loop Double Lane Changes

One of the most common criticisms of J-Turn and Fishhook maneuvers is that the handwheel inputs required to produce two-wheel lift are unreasonably large.

Any maneuver that endeavors to directly assess on-road, untripped dynamic rollover propensity must include substantial steering inputs, especially if vehicle maneuver entrance speed is to be held to a reasonably safe level.

To ascertain how the J-Turn and Fishhook maneuver handwheel inputs used in Phase IV related to those that occurred during tests performed by actual test drivers, maximum handwheel angles and rates were compared.

15.3.1 Handwheel Angles

Table 15.2 summarizes the handwheel angles used during the NHTSA J-Turns, NHTSA Fishhooks 1a and 1b, and the Nissan Fishhooks to those measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed with actual test drivers.

The largest handwheel magnitudes were used during the two Nissan Fishhook test series. This was not surprising, as these values represent the mechanical rotation limit of each vehicle's steering assembly minus 45 degrees. Neither magnitude was within the range of values measured during the closed-loop, path-following double lane changes. In the case of the Chevrolet Blazer, the maximum Nissan Fishhook steering magnitude was 15.9 and 59.2 percent greater than the overall maximum values measured during ISO 3888 Part 2 and Consumers Union Short Course testing, respectively.

The second largest handwheel magnitudes for Phase IV research occurred during Consumers Union Short Course testing. For each vehicle, these values were up to 61.7 percent greater than those used to for NHTSA J-Turns and up to 99.1 percent greater than those used to for NHTSA Fishhooks.

With the exception of the Mercedes ML320 with disabled stability control, the magnitudes of the handwheel angles used for the NHTSA J-Turns were contained within the ranges established of the maximum handwheel magnitudes measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed with that vehicle. For the ML320 with disabled stability control, the J-Turn handwheel magnitude was less than the maximum handwheel magnitude during *both* path-following, closed-loop, tests.

The handwheel angle magnitudes used for the NHTSA Fishhooks were all below the maximum handwheel magnitudes measured during the Consumers Union Short Course and ISO 3888 Part 2 tests performed with the same vehicle.

The maximum handwheel angle data presented in this section demonstrate that the magnitude of the inputs used to define the NHTSA J-Turn and Fishhook maneuvers are within the capabilities of actual, albeit skilled, drivers. However, a meaningful comparison of J-Turn and Fishhook handwheel inputs to those that occurred during closed-loop, path-following double lane changes is incomplete without the consideration of steering rates. Section 15.3.2 contains this discussion.

Table 15.2. Maximum Handwheel Angle Comparison: Automated Maneuvers Versus Closed-Loop Maneuvers (Nominal Load).

<table>
<tr><th>Vehicle</th><th>NHTSA J-Turn (degrees)</th><th>NHTSA Fishhook (degrees)</th><th>Nissan Fishhook (degrees)</th><th>Consumers Union Short Course (degrees)</th><th>ISO 3888 Part 2 (degrees)</th></tr>
<tr><td>Chevrolet Blazer</td><td>401</td><td>326</td><td>570</td><td>492</td><td>358</td></tr>
<tr><td>Toyota 4Runner (VSC)</td><td rowspan="2">354</td><td rowspan="2">287</td><td rowspan="4">Tests not performed</td><td>478</td><td>298</td></tr>
<tr><td>Toyota 4Runner (disabled VSC)</td><td>450</td><td>308</td></tr>
<tr><td>Mercedes ML320 (ESP)</td><td rowspan="2">310</td><td rowspan="2">252</td><td>400</td><td>262</td></tr>
<tr><td>Mercedes ML320 (disabled ESP)</td><td>411</td><td>323</td></tr>
<tr><td>Ford Escape</td><td>287</td><td>233</td><td>505</td><td>464</td><td>259</td></tr>
</table>

15.3.2 Handwheel Rates

When analyzing handwheel rate data, it is important to consider the duration over which the rate was sustainable. While most drivers can generate very high handwheel rates, they typically sustain them only for a very short duration.

To assess whether the Phase IV test drivers could achieve the handwheel rates used by the NHTSA J-Turn, NHTSA Fishhook, and Nissan Fishhook maneuvers, handwheel rates measured during the closed-loop, path-following double lane changes were processed with 500, 750, and 1000 millisecond running average filters during post-processing of the data. Using these data, the authors were able to determine whether the handwheel rates required by a particular J-Turn or Fishhook maneuver could be sustained by an actual driver for the required duration.

When data processed with the same running average filter durations were considered, the overall sustained peak handwheel rates during tests performed with the Consumers Union Short Course were greater than those during ISO 3888 Part 2 tests, regardless of the vehicle being considered.

During Consumers Union Short Course testing, the Phase IV test drivers were able to sustain handwheel rates of up to 1187, 1026, and 831 degrees per second for 500, 750, and 1000 milliseconds, respectively. When ISO 3888 Part 2 data were considered, these rates fell to 986, 801, and 612 degrees per second, respectively.

The handwheel rate used for all NHTSA J-Turn maneuvers performed in Phase IV was 1000 degrees per second. Since the steering angle magnitude of these maneuvers was vehicle dependent; the duration for which 1000 degrees per second had to be maintained ranged from 287 to 401 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the NHTSA J-Turn, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 500 millisecond running average filter were considered. Use of data filtered with this filter was most appropriate because its output was the average handwheel rate over a period of 500 milliseconds, slightly longer than that actually required for the NHTSA J-Turn. Since handwheel rates of up to 1187 degrees per second were sustained by test drivers for 500 milliseconds during Consumers Union Short Course testing, the authors believe that the steering rate used by the NHTSA J-Turn maneuver is within the capabilities of an actual driver.

The handwheel rate used for all NHTSA Fishhook maneuvers performed in Phase IV was 720 degrees per second. Once again, since the steering angle magnitude of these maneuvers was vehicle dependent; the duration for which 720 degrees per second had to be maintained ranged from 647 to 906 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the NHTSA Fishhooks, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 750 and 1000 millisecond running average filters were considered. For the Mercedes ML320 and Ford Escape, use of data processed with the 750 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 750 milliseconds; slightly longer than the 647 to 700 milliseconds duration actually required for the NHTSA Fishhook for these vehicles. For the Chevrolet Blazer and Toyota 4Runner, use of data processed with the 1000 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 1000 milliseconds; slightly longer than the 797 to 906 milliseconds duration actually required for the NHTSA Fishhook for these vehicles. The authors believe that because handwheel rates of up to 1026 and 831 degrees per second were sustained for 750 and 1000 milliseconds, respectively, during Consumers Union Short Course tests, the steering required by the NHTSA Fishhook maneuvers is within the capabilities of an actual driver.

The handwheel rate used for all Nissan Fishhook maneuvers performed in Phase IV was 1080 degrees per second. Like the NHTSA rollover resistance maneuvers, the steering angle magnitudes of the Nissan Fishhook were vehicle dependent; the duration for which 1080 degrees per second had to be maintained ranged from 718 to 778 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the Nissan Fishhook, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 750 and 1000 millisecond running average filters were considered. In the case of the Ford Escape, use of data processed with the 750 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 750 milliseconds; slightly longer than the 718 milliseconds duration actually required by the Nissan Fishhook for the Escape. In the case of the Chevrolet Blazer, use of data filtered with the 1000 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 1000 milliseconds; slightly longer than the 778 milliseconds duration actually required by the Nissan Fishhook for the Blazer. The authors believe that because handwheel rates of up to 1026 and 831 degrees per second were sustained for 750 and 1000 milliseconds, respectively, during Consumers Union Short Course tests, the steering required by the Nissan Fishhook maneuver may *not* be within the capabilities of an actual driver. While the Consumers Union Short Course data indicated handwheel rates of up to 1187 degrees per second were possible, the duration for which the driver was able to sustain this rate was 500 milliseconds, less than the time required for the Nissan Fishhook.

Table 15.3 compares the handwheel rates used for the NHTSA J-Turns, Fishhooks 1a and 1b, and Nissan Fishhook to sustained rates measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed with actual test drivers.

Table 15.3. Maximum Handwheel Rate Comparison: NHTSA Maneuvers Versus Closed-Loop Maneuvers (Nominal Load).

<table>
<tr><th rowspan="2">Vehicle</th><th colspan="2">NHTSA J-Turn</th><th colspan="2">NHTSA Fishhook</th><th colspan="2">Nissan Fishhook</th><th colspan="3">Consumers Union Short Course (deg/sec)</th><th colspan="3">ISO 3888 Part 2 (deg/sec)</th></tr>
<tr><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>500 ms RA</th><th>750 ms RA</th><th>1000 ms RA</th><th>500 ms RA</th><th>750 ms RA</th><th>1000 ms RA</th></tr>
<tr><td>Chevrolet Blazer</td><td rowspan="6">1000</td><td>401</td><td rowspan="6">720</td><td>906</td><td>1080</td><td>778</td><td>1187</td><td>1026</td><td>831</td><td>986</td><td>801</td><td>612</td></tr>
<tr><td>Toyota 4Runner (VSC)</td><td rowspan="2">354</td><td rowspan="2">797</td><td colspan="2" rowspan="4">Tests not performed</td><td>1030</td><td>822</td><td>784</td><td>886</td><td>722</td><td>543</td></tr>
<tr><td>Toyota 4Runner (disabled VSC)</td><td>989</td><td>815</td><td>768</td><td>800</td><td>660</td><td>535</td></tr>
<tr><td>Mercedes ML320 (ESP)</td><td rowspan="2">310</td><td rowspan="2">700</td><td>941</td><td>787</td><td>693</td><td>820</td><td>671</td><td>476</td></tr>
<tr><td>Mercedes ML320 (disabled ESP)</td><td>964</td><td>828</td><td>668</td><td>857</td><td>678</td><td>536</td></tr>
<tr><td>Ford Escape</td><td>287</td><td>647</td><td>1080</td><td>718</td><td>1049</td><td>911</td><td>766</td><td>807</td><td>682</td><td>454</td></tr>
</table>

16.0 Summary and Conclusions

16.1 Overview

This research evaluated maneuvers used to assess light vehicle dynamic rollover propensity. Even though all types of rollover are dynamic events, the focus of this investigation, dynamic rollover, is generally construed as on-road, untripped, rollover. While on-road, untripped rollovers are responsible for only a small portion of the rollover safety problem for this classification of vehicles; there are enough fatalities due to these crashes that even a small portion of the problem equates to a substantial number of fatalities per year. Further, the authors believe that Agency actions that address this type of rollover will promote rollover prevention in general.

In Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" Congress directed the National Highway Traffic Safety Administration (NHTSA) to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into NHTSA's New Car Assessment Program (NCAP) by November 1, 2002. The research described in this report has been performed as part of NHTSA's effort to fulfill the requirements of the TREAD Act.

16.2 Objectives

Prior to the initiation of the Phase IV research, NHTSA met with the Alliance of Automobile Manufacturers, Ford Motor Company, Nissan Motors, Toyota Motor Company, Consumers Union of the United States, MTS Systems Corporation, and other interested parties to gather information on possible approaches for dynamic rollover tests. NHTSA also corresponded with the University of Michigan Transportation Research Institute and Heitz Automotive, Inc. These parties made specific suggestions about approaches to dynamic testing of vehicle rollover resistance. Based on these suggestions plus NHTSA's experience in this area, the Phase IV test matrix was developed.

Phase IV testing was performed during the spring through fall of 2001. The objective of this testing was to obtain the data needed to reduce potential maneuvers to a more limited set that characterize vehicles' rollover resistance. Five Characterization maneuvers and eight Rollover Resistance maneuvers were evaluated.

Only one Characterization maneuver, Slowly Increasing Steer, is discussed in this report. The others will be discussed in a separate report.

Each Rollover Resistance maneuver was evaluated based upon its Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality. For each maneuver evaluation factor, the authors assigned a qualitative rating of Excellent, Good, Satisfactory, Bad, or Very Bad.

16.3 Work Performed

Four sport utility vehicles were tested during Phase IV, a 2001 Chevrolet Blazer, a 2001 Toyota 4Runner, a 2001 Ford Escape, and a 1999 Mercedes ML320. The 4Runner and ML320 were equipped with electronic stability control systems.

Each test vehicle was tested in three configurations. The Nominal Load configuration consisted of the driver, instrumentation, and outriggers. The Reduced Rollover Resistance configuration required sufficient weight be placed on a particular test vehicle's roof to reduce its Static Stability Factor (SSF) by 0.05. The weight on the roof was positioned so that the longitudinal/lateral position of the center of gravity did not change. Depending on the test vehicle, the Modified Handling configuration was achieved in one of two ways. The first technique was to load a vehicle to its rear Gross Axle Weight Rating (GAWR) while simultaneously achieving the Gross Vehicle Weight Rating (GVWR). The load was positioned so that it did not affect the center of gravity height or lateral position in the vehicle, only its longitudinal location. Alternatively, different tires/wheels approved/sold as OEM equipment for a particular vehicle were installed.

All Phase IV tests were performed on the Transportation Research Center, Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The test surface was paved with asphalt of a mix representative of that used to construct many Ohio highways. All Phase IV tests were performed on dry pavement.

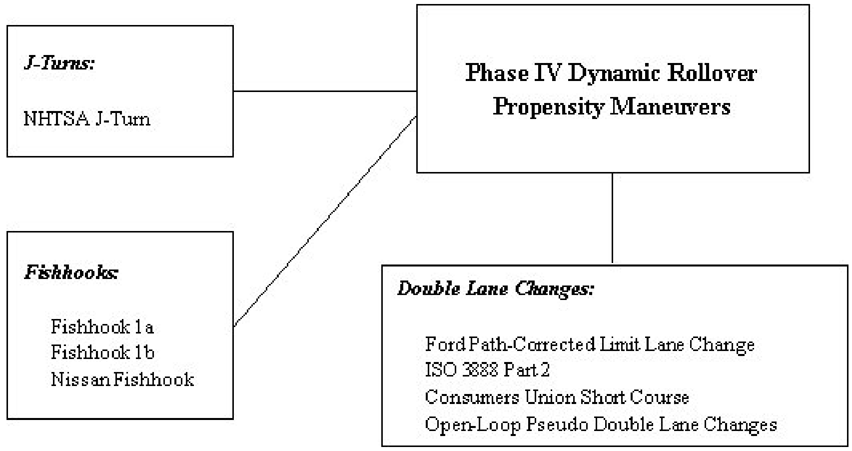
Unlike previous phases, the authors decided not to consider or report minor two-wheel lift in Phase IV. Its occurrence was no longer used as a termination condition for rollover resistance maneuvers. Furthermore, the authors decided not to differentiate between moderate and major two-wheel lift. In this report the term two-wheel lift was used to indicate that either moderate or major two-wheel lift was observed.

16.4 Characterization Maneuvers

Five Characterization Maneuvers were studied during the Phase IV research. The Pulse Steer, Sinusoidal Sweep, Slowly Increasing Steer, Slowly Increasing Speed, and J-Turn Response Time test series each included tests performed with the Nominal Load, Reduced Rollover Resistance, and Modified Handling configurations. A programmable steering machine was used to command all Characterization Maneuver handwheel inputs. This report summarized results obtained from the Slowly Increasing Steer tests, and how the subsequent data is used to define NHTSA J-Turn and Fishhook handwheel input magnitudes. For the sake of brevity, results from the other Characterization Maneuvers will be discussed in a later report.

16.5 Rollover Resistance Maneuvers

Eight Rollover Resistance maneuvers were evaluated during the Phase IV research. The maneuvers evaluated were:



A programmable steering machine was used to generate J-Turn, Fishhook, and Open-Loop Pseudo Double Lane Change handwheel inputs. The other three maneuvers were path-following maneuvers with driver-generated, closed-loop, steering. Multiple test drivers were used for the maneuvers with closed-loop steering.

Depending on the maneuver, the test vehicles were evaluated with up to three configurations per maneuver (Nominal Load, Reduced Rollover Resistance, and Modified Handling).

Table 16.1 summarizes the scores assigned to each Rollover Resistance maneuver in the areas of Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality.

Table 16.1. Summary of Rollover Resistance Maneuver Scores.

Assessment Criterion	NHTSA J-Turn	Fishhook 1a	Fishhook 1b	Nissan Fishhook	Ford Path-Corrected Limit Lane Change	ISO 3888 Part 2 Double Lane Change	Consumers Union Short Course Double Lane Change	Open-Loop Pseudo-Double Lane Change
Objectivity and Repeatability	Excellent	Excellent	Excellent	Good	Bad	Bad	Bad	Satisfactory
Performability	Excellent	Good	Excellent	Satisfactory	Satisfactory	Good	Satisfactory	Satisfactory
Discriminatory Capability	Excellent*	Excellent	Excellent	Excellent	Good	Very Bad	Very Bad	Very Bad
Appearance of Reality	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

* When limited to vehicles with low rollover resistance and/or disadvantageous load condition.

Table 16.2 summarizes the two-wheel lifts that occurred during the Phase IV testing. No two-wheel lift was observed during any “clean” (no cones struck or bypassed) path following, closed-loop steering, double lane change maneuver (i.e., for the ISO 3888 Part 2 and Consumers Union Double Lane Changes), even when the vehicles were evaluated in the Reduced Rollover Resistance condition.

Table 16.2. Minimum Maneuver Entrance Speed Resulting in Two-Wheel Lift (mph).

Vehicle	J-Turn	Fishhook 1a	Fishhook 1b	Nissan Fishhook	Ford Path-Corrected Limit Lane Change	ISO 3888 Part 2 Double Lane Change	Consumers Union Short Course Double Lane Change	Open-Loop Pseudo-Double Lane Change	
								Simulated CU Short Course Double Lane Change	Simulated ISO 3888 Part 2 Double Lane Change
2001 Chevrolet Blazer	-- (38.9[1])	40.2 (36.2[1])	40.1 (36.2[1], 34.9[2])	46.1	--	-- (--[1])	--	48.2	54.0
2001 Toyota 4Runner (enabled VSC)	-- (--[1])	-- (47.6[1])	-- (49.6[1], --[2])	Tests not performed.	--	-- (--[1])	--	--	--
2001 Toyota 4Runner (disabled VSC)	-- (46.1[1])	-- (38.4[1])	-- (37.7[1], --[2])		--	-- (--[1])	--	--	42.9
1999 Mercedes ML320 (enabled ESP)	-- (50.9[1])	47.8 (N/A[1])	49.9 (N/A[1], 51.7[2])		--	-- (--[1])	--	Tests not performed.	
1999 Mercedes ML320 (disabled ESP)	-- (45.1[1])	43.5 (N/A[1])	46.4 (N/A[1], 51.3[2])		--	-- (--[1])	--		
2001 Ford Escape	-- (--[1])	-- (48.4[1])	-- (46.0[1], --[2])	--	--	-- (--[1])	--		

Note: Unless indicated, the results presented in Table 2 were observed in the Nominal Load configuration

[1]Reduced Rollover Resistance configuration

[2]Modified Handling configuration

Table 16.3 compares handwheel angles used for the NHTSA J-Turn, Fishhooks 1a and 1b, and the Nissan Fishhooks to those measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed by actual test drivers. The largest handwheel magnitudes were used during the Nissan Fishhook test series. Neither magnitude was within the range of values measured during the path following, closed-loop, double lane changes.

Of the path following, closed-loop, maneuvers, the larger handwheel angle magnitudes occurred during Consumers Union Short Course testing. For each vehicle, these values were up to 61.7 percent greater than those used to command NHTSA J-Turns and up to 99.1 percent greater than those used to command NHTSA Fishhooks.

With the exception of the Mercedes ML320 with disabled stability control, the magnitudes of the handwheel angles used for the NHTSA J-Turns were contained within the ranges established of the maximum handwheel magnitudes measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed with that vehicle. For the ML320 with disabled stability control, the J-Turn handwheel magnitude was less than the maximum handwheel magnitude during *both* path-following, closed-loop, tests.

Table 16.3. Maximum Handwheel Angle Comparison: Automated Maneuvers vs. Closed-Loop Maneuvers (Nominal Load).

<table>
<tr><th>Vehicle</th><th>NHTSA J-Turn (degrees)</th><th>NHTSA Fishhook 1a / 1b (degrees)</th><th>Nissan Fishhook (degrees)</th><th>Consumers Union Short Course (degrees)</th><th>ISO 3888 Part 2 (degrees)</th></tr>
<tr><td>Chevrolet Blazer</td><td>401</td><td>326</td><td>570</td><td>492</td><td>358</td></tr>
<tr><td>Toyota 4Runner (VSC)</td><td rowspan="2">354</td><td rowspan="2">287</td><td rowspan="4">Tests not performed</td><td>478</td><td>298</td></tr>
<tr><td>Toyota 4Runner (disabled VSC)</td><td>450</td><td>308</td></tr>
<tr><td>Mercedes ML320 (ESP)</td><td rowspan="2">310</td><td rowspan="2">252</td><td>400</td><td>262</td></tr>
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<tr><td>Ford Escape</td><td>287</td><td>233</td><td>505</td><td>464</td><td>259</td></tr>
</table>

When analyzing handwheel rate data, it is important to consider the duration over which the rate was sustainable. While most drivers can generate very high handwheel rates, they typically sustain them only for a very short duration.

To assess whether the actual drivers used in Phase IV could achieve the handwheel rates required by the NHTSA J-Turn, Fishhook 1a and 1b, and Nissan Fishhook maneuvers, handwheel rates observed during the closed-loop, path-following double lane changes were processed with 500, 750, and 1000 millisecond running average filters during post-processing of the data. Using these data, the authors were able to determine whether the handwheel rates required by a particular J-Turn or Fishhook maneuver could be sustained by an actual driver for the required duration.

The handwheel rate used for all NHTSA J-Turn maneuvers performed in Phase IV was 1000 degrees per second. Since the steering angle magnitude of these maneuvers was vehicle dependent; the duration for which 1000 degrees per second had to be maintained ranged from 287 to 401 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the NHTSA J-Turn, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 500 millisecond running average filter were considered. Use of data filtered with this filter was most appropriate because its output was the average handwheel rate over a period of 500 milliseconds, slightly longer than that actually required for the NHTSA J-Turn. Since handwheel rates of up to 1187 degrees per second were sustained by test drivers for 500 milliseconds during Consumers Union Short Course testing, the authors believe that the steering rate used by the NHTSA J-Turn maneuver is within the capabilities of an actual driver.

The handwheel rate used for all NHTSA Fishhook maneuvers performed in Phase IV was 720 degrees per second. Once again, since the steering angle magnitude of these maneuvers was vehicle dependent; the duration for which 720 degrees per second had to be maintained ranged from 647 to 906 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the NHTSA Fishhooks, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 750 and 1000 millisecond running average filters were considered. For the Mercedes ML320 and Ford Escape, use of data processed with the 750 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 750 milliseconds; slightly longer than the 647 to 700 milliseconds duration actually required for the NHTSA Fishhook for these vehicles. For the Chevrolet Blazer and Toyota 4Runner, use of data processed with the 1000 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 1000 milliseconds; slightly longer than the 797 to 906 milliseconds duration actually required for the NHTSA Fishhook for these vehicles. The authors believe that because handwheel rates of up to 1026 and 831 degrees per second were sustained for 750 and 1000 milliseconds, respectively, during Consumers Union Short Course tests, the steering required by the NHTSA Fishhook maneuvers is within the capabilities of an actual driver.

The handwheel rate used for all Nissan Fishhook maneuvers performed in Phase IV was 1080 degrees per second. Like the NHTSA rollover resistance maneuvers, the steering angle magnitudes of the Nissan Fishhook were vehicle dependent; the duration for which 1080 degrees per second had to be maintained ranged from 718 to 778 milliseconds. To assess whether the actual drivers used in Phase IV could achieve the handwheel rate used by the Nissan Fishhook, Consumers Union Short Course and ISO 3888 Part 2 data processed with the 750 and 1000 millisecond running average filters were considered. In the case of the Ford Escape, use of data processed with the 750 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 750 milliseconds; slightly longer than the 718 milliseconds duration actually required by the Nissan Fishhook for the Escape. In the case of the Chevrolet Blazer, use of data filtered with the 1000 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 1000 milliseconds; slightly longer than the 778 milliseconds duration actually required by the Nissan Fishhook for the Blazer. The authors believe that because handwheel rates of up to 1026 and 831 degrees per second were sustained for 750 and 1000 milliseconds, respectively, during Consumers Union Short Course tests, the steering required by the Nissan Fishhook maneuver may *not* be within the capabilities of an actual driver. While the Consumers Union Short Course data indicated handwheel rates of up to 1187 degrees per second were possible, the duration for which the driver was able to sustain this rate was 500 milliseconds, less than the time required for the Nissan Fishhook.

Table 16.4 compares the handwheel rates used for the NHTSA J-Turn, Fishhooks 1a and 1b, and Nissan Fishhook to sustained rates measured during Consumers Union Short Course and ISO 3888 Part 2 tests performed with actual test drivers.

Table 16.4. Maximum Handwheel Rate Comparison: Automated Maneuvers vs. Closed-Loop Maneuvers (Nominal Load).

<table>
<tr><th rowspan="2">Vehicle</th><th colspan="2">NHTSA J-Turn</th><th colspan="2">NHTSA Fishhook 1a / 1b</th><th colspan="2">Nissan Fishhook</th><th colspan="3">Consumers Union Short Course (deg/sec)</th><th colspan="3">ISO 3888 Part 2 (deg/sec)</th></tr>
<tr><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>Rate (deg/sec)</th><th>Duration (ms)</th><th>500 ms RA</th><th>750 ms RA</th><th>1000 ms RA</th><th>500 ms RA</th><th>750 ms RA</th><th>1000 ms RA</th></tr>
<tr><td>Chevrolet Blazer</td><td rowspan="6">1000</td><td>401</td><td rowspan="6">720</td><td>906</td><td>1080</td><td>778</td><td>1187</td><td>1026</td><td>831</td><td>986</td><td>801</td><td>612</td></tr>
<tr><td>Toyota 4Runner (VSC)</td><td rowspan="2">354</td><td rowspan="2">797</td><td colspan="2" rowspan="4">Tests not performed</td><td>1030</td><td>822</td><td>784</td><td>886</td><td>722</td><td>543</td></tr>
<tr><td>Toyota 4Runner (disabled VSC)</td><td>989</td><td>815</td><td>768</td><td>800</td><td>660</td><td>535</td></tr>
<tr><td>Mercedes ML320 (ESP)</td><td rowspan="2">310</td><td rowspan="2">700</td><td>941</td><td>787</td><td>693</td><td>820</td><td>671</td><td>476</td></tr>
<tr><td>Mercedes ML320 (disabled ESP)</td><td>964</td><td>828</td><td>668</td><td>857</td><td>678</td><td>536</td></tr>
<tr><td>Ford Escape</td><td>287</td><td>647</td><td>1080</td><td>718</td><td>1049</td><td>911</td><td>766</td><td>807</td><td>682</td><td>454</td></tr>
</table>

16.6 Conclusions

Thirty years ago, NHTSA began studying dynamic rollover propensity maneuvers. At that time, the conclusion reached was that the maneuvers being studied had such major problems, particularly in the area of objectivity and repeatability, as to preclude their use by the Government. Today, following much effort, this is no longer the case. As can be seen from Table 16.1, four of the Rollover Resistance maneuvers have a rating of satisfactory or better in each of the four maneuver evaluation factors. In the authors' opinion, these four maneuvers are good enough that they could be used by the Government for consumer information.

Four of the eight rollover maneuvers were rated satisfactory or better in each of the four evaluation criteria. These maneuvers were:

- NHTSA J-Turn
- NHTSA Fishhook 1a
- NHTSA Fishhook 1b
- Nissan Fishhook

Of the four better performing maneuvers, Fishhook 1b was the best overall.

The NHTSA J-Turn is the most basic of potential maneuvers (a single step-steer input), could be a useful complement to Fishhook 1b.

The double lane change courses used in Phase IV were not optimized for the evaluation of dynamic rollover propensity. It is very likely that the layout of these courses affected the vehicles in different ways, regardless of whether course dimensions were adapted to the vehicles on a per-vehicle basis (i.e., lane widths). Differences in vehicle handling were inevitably introduced, and potentially confounded the evaluation of rollover propensity during the closed-loop, path-following double lane changes.

The handwheel input rates and magnitudes of the NHTSA J-Turn and Fishhook 1b are within the capabilities of an actual driver.

So as to improve understanding of the scenario Fishhook 1b endeavors to emulate, the maneuver will be renamed. Fishhook 1b will henceforth be known as the "NHTSA Road-Edge Recovery Maneuver."

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